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POWER-FACTOR WASTES

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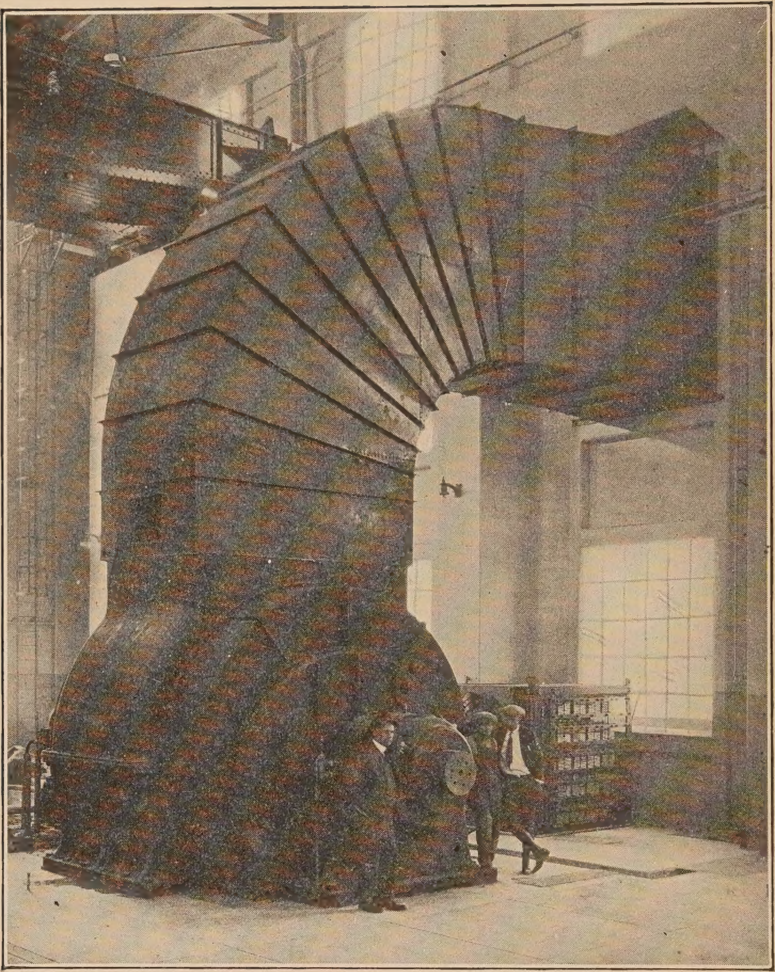

(*Frontispiece.*)

30,000-kva. synchronous condenser, Laguna Bell Substation, Southern California Edison Company. (*Courtesy of Westinghouse Electric and Manufacturing Company.*)

POWER-FACTOR WASTES

A Practical Book for Manufacturing Executives, Plant Engineers and Electricians.

BY
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TO ALL THOSE

WHO, IN WHATEVER MANNER,

HELPED TO PRODUCE THIS BOOK

PREFACE

The generation and distribution of electric energy started in a modest way for lighting only, a direct current of electricity that flowed somewhat like a belt from a driving to a driven pulley being employed. To ascertain the magnitude of the electric power, it was only necessary to measure the current strength in amperes and multiply it by the measured supply voltage. The amount of electric energy sold to a customer during a given period was taken as the product of the average supply voltage and the quantity of electricity that flowed through the meter on the customer's premises during the same period. The wattmeter and the watt-hour meter were developed and used respectively for measuring electric power and the electric energy delivered and consumed.

With the use of the alternating current of electricity that alternately and periodically flows to and fro in its circuit, new instruments were devised for the measurement of the effective current strength and the effective supply voltage. Then followed the familiar alternating-current watt-hour meter as applied to the measurement of electric energy thus transmitted and consumed. The adoption of the alternating-current system of electric transmission brought forth the transformer with the subsequent higher transmission voltages and the reduction in line wire investment and in line losses, thus making possible the relatively long-distance transmission lines of today.

Before the advent of the transformer, the power in an alternating-current system could be approximately determined by multiplying the number of amperes by the supply voltage. With the introduction of transformers, however, the product of the measured number of amperes and the measured supply voltage always was much greater than the electric power as indicated by the wattmeter. Loads that easily could be carried by one electric generator before the utilization of the transformer, as during the daylight hours, now required two or more generators to carry the same load with the supply voltage the same in both cases. Yet the total output of the steam engines driving the generators was but little more than that required of one of the engines when driving one generator to carry the full load in the absence of the transformers.

It was found that a part of the total current was working under the driving pressure of the supply voltage to produce light in the lamps and to heat the transmission and distribution wires somewhat, but that the greater part of the total current was required simply to magnetize the steel in the transformers. Hence there are two currents in the same wires in alternating-current generating, transmission and distribution systems, namely, the *working current* which does the work, and the *magnetizing current* which magnetizes steel when an inductive coil of insulated wire is wound around it. Fundamentally, one generator might supply all the magnetizing current and a second generator might supply all the working current.

The triumphal entry of the induction motor into the industries made operating conditions even worse, because of its preemptory demand for magnetizing current in proportion to working current when running underloaded, and the cross-sections of all line and other wires had to be increased, thus increasing the dimensions of the generators, transformers and other electrical equipment containing coils of insulated wire. Obviously, this required an additional capital investment, and the magnetizing current still interferred with good service to the power users.

As the inductive loads increased, means were employed to supply magnetizing current from the substation, instead of entirely from the central station, to keep much of the magnetizing current out of the generator coils and lines so that their dimensions would not have to be increased as by purchasing and installing more duplicate electrical equipment—and excellent returns on the investment were realized.

But the magnetizing current still remained in the distribution systems of both the utility and the consumer. Certain electric public utilities found it expedient to offer financial inducements to large power users to keep the ratio (power factor) of working current to total current high by supplying their own magnetizing current on their own premises, thus relieving the utilities' distribution feeders and transformers of the burden of carrying much of the magnetizing current—and both the utilities and their customers found that it paid.

Within the industrial plant, however, conditions were not improved, except for better voltage regulation, and the losses in the plant's electric distribution system and in production still continue, excepting in such relatively few cases where power-factor corrective apparatuses have been installed or where motors with inherently high power factors are utilized to good advantage —and power users find that this also pays.

The foregoing is due to the fact that underloaded induction motors and transformers require more magnetizing current than working current, and that an electric public utility renders two kinds of service, namely, the *energy service* and the *magnetizing service.*

The fundamental cause is very simple, yet the effects involve serious questions of finance and executive management. The fact that small power users are given magnetizing service while large power users must pay for it, or else supply it at their own expense, has produced an unfortunate situation of class discrimination.

Power-factor wastes is a vital subject to the power users as well as to the electric public utilities and, indirectly, to all consumers of electric energy.

One object of this book is to acquaint those directly responsible for a large proportion of power-factor wastes, and who pay the bills therefor, how much they cost, as reflected in actual saving, their causes and cures, as proved by experience, and the opinions of a number of authorities, including some of the members of those vast organizations supplying electric service. Naturally, these views may differ, but the aim is to present as many sides of the question as practicable so that all may learn through the broad discussion. Another object is to form a sort of nucleus on the general subject, since former publications largely have been in the forms of articles or papers and, therefore, are widely scattered.

With these ends in view, the subject is treated in a simple manner with the hope that manufacturing executives, plant engineers and electricians readily may grasp the information they desire, and that utility executives and engineers also may find information of value.

Too high tributes cannot be paid the men of genius, vision, enterprise, and courage, who have brought forth and developed this inestimable service for the benefit of mankind. But the work is not yet finished.

The text is written partly by contributors, partly by various authorities whose original writings appeared elsewhere, and partly by the author-editor whose approach is through the induction motor. Full credit for all material is given in the proper places.

CHARLES R. UNDERHILL.

NEW YORK, N. Y.
January, 1926.

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POWER-FACTOR WASTES

CHAPTER I

INTRODUCTORY

In order to understand the cause of low power factor and how to correct that cause, it is necessary to split the total current in an induction motor, for instance, into its two components. Following a discussion of this subject, the power factor, induction motors, synchronous motors, and a combination of synchronous and induction motor, together with some forms of power-factor-improving apparatus, are considered.

1. Electric Motors and Electric Currents.—Electric motors have two general parts, one of which remains stationary while the other revolves. The fundamental principle upon which all electric motors operate is that an electric current produces magnetism in the motor while another, or the same, electric current reacts upon the magnetism to run the motor. Hence, as a general proposition, there is a magnetizing current which magnetizes the motor, and there is also a running current which runs the motor, under the actions of the electric pressures or voltages that move the electricity in the wires.

In direct-current motors, the electricity flows in one direction only, and the motor remains magnetized as long as the electricity flows. When the switch is opened, however, the motor becomes demagnetized.

An alternating-current motor of the induction type is magnetized and then demagnetized each time the current alternates.

This general principle constitutes the primary cause of all power-factor wastes.

In alternating-current generators and synchronous motors, the magnetizing current is supplied in each case by a small direct-current generator, called an exciter, which sometimes is driven through the medium of a belt by the alternating-current generator or by the synchronous motor. There is no fundamental difference between an alternating-current generator and a synchronous motor. An alternating-current generator may run as a synchronous motor to drive machinery, or as a synchronous condenser when not driving a load. In such cases, the strength of the magnetizing current can be separately measured by connecting an ammeter in the exciter circuit. Such machines generate their own magnetizing current.

In induction motors, however, both the magnetizing and running currents are in the wires common to both currents; so they cannot be separately measured by connecting an ammeter in the wires leading to the induction motors. Only the total current strength in amperes can thus be measured.

An exciter is a part of a synchronous motor. When a synchronous motor is connected in a system, the power required to drive the exciter to magnetize the motor is indicated, along with the running power, on a kilowatt meter because all of the energy flows in one direction from the line to the synchronous motor and thence to the exciter, as well as to the load, since the synchronous motor drives the exciter. Hence, all of the energy that flows from the line to a synchronous motor, both for magnetizing and running it, may be measured by means of a kilowatt-hour meter when the exciter and load are properly adjusted. Such measurements also include the energy lost in the form of heat in the wires, and so forth, between the kilowatt-hour meter and the motor.

An induction motor cannot supply its own magnetizing current. The magnetizing current must be supplied from the central station unless some form of power-factor-improving apparatus is connected at or near the motors. The object of power-factor correction is to relieve the central station from supplying the magnetizing current. When an induction motor is connected in a system, the energy that runs the motor flows in one direction only, that is, from the line to the motor and thence through the shaft and any belting to the various machines, while the magnetizing energy that magnetizes the motor through the medium of the magnetizing current flows to and from the motor as the latter alternately is magnetized and demagnetized.

The switchboard ammeter gives absolutely no indication as to how many amperes are magnetizing induction motors and how many are actually running them, since only the total number of amperes is indicated. This might all be magnetizing current while one might *think it* all running current, although both are present.

2. The Power Factor.—Power factors may be expressed as percentages of the current actually running a motor to the current actually flowing in the motor. Where the voltage at the motor terminals is constant, the wave form is sinusoidal, and the current strength in all of the wires connected to the motor is constant and of the same value, the power factor is equal to the ratio of the running current to the total current. This holds directly for single-phase induction motors.

For two-phase and three-phase induction motors, constants must be introduced. There are other technical features.

When the running current is equal to the total current, which condition may be obtained with a synchronous motor by adjusting its excitation and load, or with a synchronous condenser by simply adjusting its excitation, the power factor is unity, or 100 per cent.

When the magnetizing current is equal to the running current, the power factor is 70.7 per cent. The author has corrected the plant power factor to a value greater than the above by simply changing the induction motors around so that the loads carried by them were more suitable for the operating characteristics of the motors.

When the magnetizing current is equal to the total current, the power factor is equal to zero, and a motor with a zero power factor cannot run because there is then no running current. This is a purely theoretical proposition, however, since all motors have power factors greater than zero.

When the power factor of a motor is 100 per cent, no magnetizing current exists in the lines or other wires leading to the motor, and induction motors cannot run under such circumstances. Such a condition may be obtained with a Fynn-Weichsel motor which, just now, may generally be defined as a combination induction and synchronous motor with the exciter built into the machine, and which starts as an induction motor but runs as a synchronous motor and simultaneously overcomes low power factors due to induction motors connected in the system, thus increasing the plant power factor to a high value. This motor, like the synchronous motor, can run at unity power factor because it supplies its own magnetizing current.

In spite of the fact that induction motors may have fair power factors when driving loads suitable for induction motors, plant power factors may be found as low as 40 per cent or less, but they may be corrected to 80 per cent or more.

In induction motors, the magnetizing current does not increase so rapidly as the running current with respect to the load on the motor; so the power factor increases with the load. In one type of 25-hp. squirrel-cage polyphase induction motor, the power factor may be increased from 84 to 91 per cent by increasing the rated load of the motor from one-half to full load. Hence, to change a large proportion of the total current into running current, make the induction motors work by using the right motor on the right drive. The author can see no reasonable excuse for applying such sizes of induction motors with low speeds to drives that are wholly unsuited to the operating characteristics of the induction motors thus installed. If an induction motor is not suitable for a given drive, why use an induction motor at all? As far as may be found practicable, make the induction motors draw the full-rated-load amperes at the rated voltage right at the motor terminals. If a motor is old or has been repaired, however, the name-plate data may not mean much. If the voltage is not constant, the probabilities are that either the proportion of magnetizing current in the distribution system is excessive, the distribution-system wires and cables are too small for the current drawn by the motors, production is somewhat decreased due to the reduced speeds of the motors having low voltage at their terminals, or some of the product is made defective due to variations in speed. Some of the conditions apply to certain industrial plants and some to others; sometimes the voltage regulation at the meter is good and sometimes it is poor, but if any of the above items appear in any industrial plant some money is being wasted. While there may not be great variations in the speeds of induction motors when the voltage is correct and is constant, when loads increase and the voltage decreases, the speed is decreased.

Here is the first rule for increasing the power factor where induction motors already are installed: Load the motors as much as practicable by changing the motors around so that the operating characteristics of the motors used shall be suitable for the duty cycles of their new drives. If induction motors are unsuitable for some of these drives, do not use an induction motor.

There has been altogether too much blame placed on the induction motor when the blame more often belongs somewhere else. Loading induction motors changes a larger proportion of the total current into running current. Such improvements are often accomplished simply by making the loafing induction motors do the work they were originally intended to do, or else by substituting smaller motors for the large ones so that the smaller motors will be properly loaded when doing the work formerly done by the big loafers. This does not mean that the motors should be excessively overloaded. However, overloaded induction motors generally are few as compared to the number of underloaded induction motors, 7½-hp. induction motors doing the work formerly done by 25-hp. induction motors in some cases. Such a method increases the power factor by reducing the demand for magnetizing current, since smaller motors usually replace the larger ones.

The terms "low power factor," "excessive proportion of magnetizing current," and "underloaded induction motors" have a common practical meaning—right in the shops where they are used.

The general term "power factor" may refer to that of an individual motor, of a group of motors, or of an entire plant. The latter is called the plant power factor.

Just as an entire plant or an entire system of plants may have a low power factor when some of the individual power factors are high and some are low, so may two adjacent plants have a mutually low power factor when the inherent power factor of one of the plants may be good and the other low. This may be due to magnetizing current flowing from the plant with the inherently good power factor to the plant with the inherently poor power factor. To quote a part of an advertisement for power-factor-corrective apparatus: "You've lectured me on power-factor correction and duty to my customers," said the power salesman. "Why don't you stop playing both ends against the middle on the Smith Street substation?" "What?" said the Chief Engineer. "Oh, you mean the way I've balanced the lagging reactives in the Jones plant with the leading reactives in the Arctic plant." "Yes," said the power salesman. "You stepped in and insisted on the Arctic people installing all synchronous motors and over-exciting them to supply magnetizing current for Jones' induction motor load."

Low-speed induction motors are larger than high-speed induction motors having equal rated horsepower outputs, with proportionately lower power factors. Therefore, use 1,800 and 1,200 r.p.m. induction motors whenever practicable.

3. Some Reasons for Running Induction Motors Underloaded. When induction motors are purchased or installed, good guesses are not always made as to load conditions. Therefore, the factors of safety allowed are usually sufficient to make the motors run underloaded, with resulting low power factors. Some loads require larger motors to start them than to run them. Seasonable variations in trade cause motors to be run underloaded during dull times. Many machines have working cycles that require more power during certain portions of these cycles than at other times, and thus are wholly unsuitable as induction-motor drives. When such machines are driven by induction motors, the average power factor is low. However, if such machines can be driven along with other machines by a common motor, or if the individual motor is run overloaded a part of the time, better average power factors may be obtained. It is a case of loading the induction motors as much as possible in an intelligent manner. In some factories, loads are shifted by means of belts connecting different line shafts so as to cause a loafing motor to help out one that may become overloaded through the addition of driven machines, or so that certain motors may be shut down in dull seasons. As one chief electrician in a fairly large industrial plant said to the author: "Whenever I find a 25-hp. motor loafing, I yank it out quick and put in a 15-hp. motor."

4. The Power User is Largely Responsible for Low Power Factor.—Excessive proportions of magnetizing current originate on the premises of the power user who pays the whole cost therefor. Transformers and other inductive apparatuses not equipped with magnetizing-current-supplying devices are contributing causes of the excessive magnetizing current in addition to that caused by induction motors.

5. Sources of Supply of Magnetizing Current.—For induction motors and the like, the magnetizing current must be supplied from the central-station generators, unless power is generated on the premises or power-factor-correction methods are employed. The magnetizing current causes both reactive and heating effects; so when it comes from the central-station generators to magnetize induction motors and the like, the utilities' lines and general electric equipment must carry more total current than is required to run synchronous motors for the same amount of power, and the reactive effects caused by the magnetizing current are productive of reduced and variable voltages at the consumers' meters and at the motor terminals. There is then said to be a "reactance drop" in voltage.

When only motors of the synchronous or synchronous-induction types operating at unity power factor, are driven by power from a central station, practically all of the current is running current, there is substantially no reactance drop, and the voltage tends to remain constant at the consumers' meters. Too small wires in an industrial-plant distribution system, however, may cause a "resistance drop" in voltage which may make the voltage at the motor terminals less than that at the plant terminals, or meter, and the voltage at the motor terminals also may vary.

The source of supply of the magnetizing current in a synchronous motor is the direct-current generator or exciter which may be considered a part of the synchronous motor. In the synchronous-induction type, the exciter is built into the motor.

6. Static Condensers.—When these are suitably connected across the terminals of each motor having a low power factor due to some cause that cannot be corrected by loading the motor, or when a power factor in excess of the full-rated-load power factor of the motor is required, the greater part of the magnetizing current comes from the central station only long enough to magnetize the motor during the first quarter cycle—about $\frac{1}{240}$ sec. for a 60-cycle system. Thereafter, most of the energy required to magnetize the motor is discharged from the motor to the condenser, which catches it and hurls it back to the motor to magnetize it again as the current reverses.

Hence, the static condenser may be considered a source of supply of magnetizing current, and its net effect is comparable to that of the exciter of a synchronous motor, only it has no moving parts.

When directly connected across the motor terminals, the static condenser keeps much of the magnetizing current out of the industrial-plant distribution system and the utilities' lines and general electrical equipment clear back into the central-station generators, and thus saves money that otherwise would be lost due to the heat caused by the magnetizing current in the wires, cables, and general electrical equipment clear back to the central station, and also releases some of the entire electric equipment for carrying running current. This also tends to improve the voltage regulation.

In some cases, it does not pay to increase the power factor above about 95 per cent because of the increasing expense of connective apparatus as the power factor approaches unity.

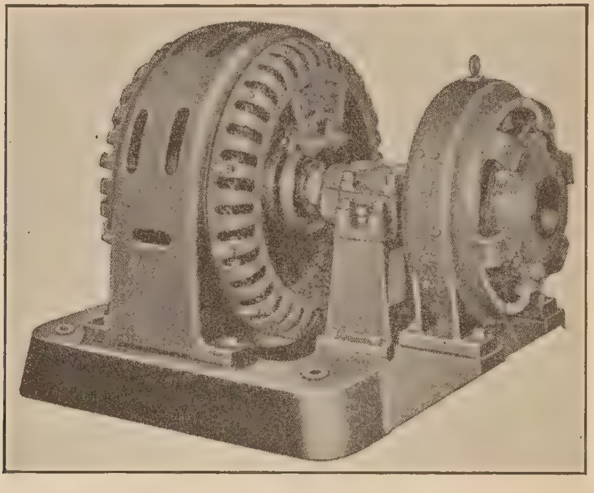

Fig. 1.—Engberg alternating-current generator with direct-connected (direct-current) exciter.

When static condensers or synchronous condensers are connected across the plant terminals or at the load center, as at the meter, the magnetizing current is not eliminated from the plant distribution system. There is just as much magnetizing current as before.

Since the induction motor is the chief cause of low power factor, it would appear that the best place to improve the power factor is at the source of excessive magnetizing current.

7. Synchronous Condensers.—These are sometimes called idle alternators or idle generators because the latter are often used as synchronous condensers. The only function of a synchronous condenser is to supply magnetizing current, something after the manner of a static condenser but through electromagnetic means. Although it may do no useful mechanical work, it requires as much attendance as a motor.

The term "synchronism" means "in step," "in tune," or "in phase." A number of alternating-current generators operating in parallel must all deliver the voltage in phase as a common voltage. By adjusting the proportion of running current and magnetizing current produced by each generator, the running current may be nearly eliminated from one generator, when it may be disconnected from its engine or turbine, and the generator will keep on running in synchronism but now as a motor, and will draw only sufficient running current from the other generators to overcome its bearing friction, air resistance, and so forth, but will continue to supply magnetizing current to the line along with the other generators.

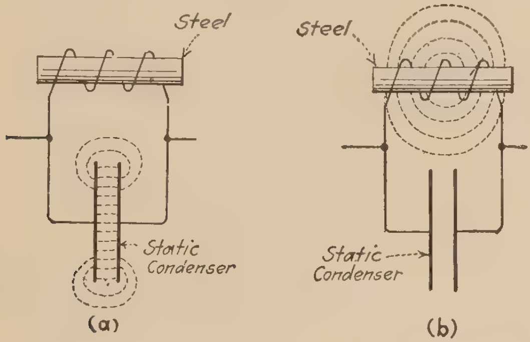

FIG. 2.—Alternate storage and transfer of energy. *a*. Energy previously stored in steel now stored in paper of static condenser. *b*. Energy previously stored in condenser now stored in steel.

If the power factor is 80 per cent and one generator will supply both the magnetizing and running currents, two similar generators will be required when the power factor is 40 per cent; the magnetizing and running currents being supplied by both machines in various proportions.

8. Synchronous Motors.—These are fundamentally the same as alternating-current generators but are driven as motors. When they carry no loads, they run as synchronous condensers and draw very little running current from the line but supply magnetizing current. As these motors are gradually loaded, they draw more running current from the line and supply less magnetizing current. Synchronous motors may earn most of their maintenance by doing mechanical work and simultaneously supplying magnetizing current, but they require more attention than induction motors; they do not generally start well like induction motors, and they stop running if overloaded beyond a critical limit even for a very brief period of time.

9. The Fynn-Weichsel Motor.—This motor combines the features of the synchronous motor with those of the induction motor, having the ability to supply magnetizing current combined with the starting characteristics of a ship-ring induction motor. Furthermore, it has great ability to carry overloads. It may be used as an industrial motor where a constant-speed induction motor would be used. These motors are sometimes installed on a fifty-fifty basis, as to horsepower output, with induction motors, and also are used to carry their own loads and simultaneously correct the power factor of a group of small motors, and so forth.

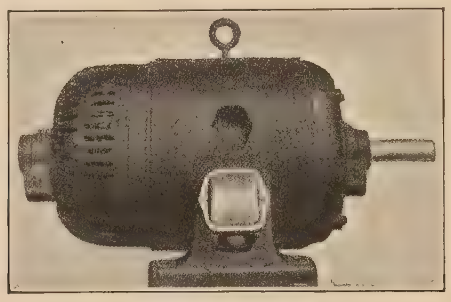

Fig. 3.—Fynn-Weichsel motor.

10. The Induction Motor.—This motor, the invention of Nikola Tesla, is designed to operate with single-phase and polyphase currents. Squirrel-cage induction motors are used much more than any other type of induction motor, about 90 per cent of all of the induction motors made in the United States being of this type. Squirrel-cage polyphase induction motors are very extensively used in all branches of industry where variable speeds are not required, and are made in sizes varying from a fraction of a horsepower to 10,000 hp. It is the extensive use and misuse of these motors that has brought about the present power-factor situation. This motor is too common to require description at this place except to state that there are no brushes of any sort. The only moving parts that come into contact are the ends of the shaft at the bearings; they are simple and rugged, have low first cost and long life, fairly constant speed at all loads with the rated voltage, and moderate starting torque, and possess inherent power-factor-corrective characteristics of their own which make it possible to increase the power factors up to good values by simply loading the motors. Table I gives the power factors of some squirrel-cage polyphase induction motors of various makes. There can be little doubt that the tendency towards individual drive has called for the development of low-speed induction motors.

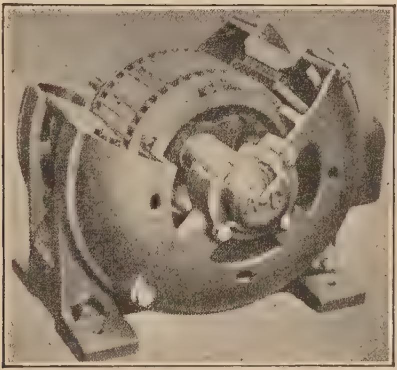

FIG. 4.—Allis-Chalmers squirrel-cage polyphase induction motor equipped with Timken tapered roller bearings for grease lubrication designed for driving crushers and grinders and for hard service in general.

The following editorial by F. A. Annett appeared in *Power* on Sept. 15, 1925:

NOT SO BAD AS IT MAY APPEAR

The induction motor, although the most reliable and simplest type of motor developed for industrial service, has come into more or less bad repute on account of its power-factor characteristics. Low power factors of power systems are not altogether due to the induction motor. The lack of proper consideration to its applications has been an even larger factor. If, on account of not knowing what power the duty cycle of a load requires, a motor of two or three times the capacity necessary to do the work is installed, the machine should not be blamed for the human shortcomings. In many installations, material improvements have been made in the power factor by rearranging the motors so as to get them more nearly loaded and by substituting new motors for a few that, on account of their size, could not be properly applied.

What was accomplished in the rearrangement of the motors should have been done at first and the expense of the change saved.

Contrary to the general opinion, the power factor of a normal induction motor at full load or even at half load would not be considered low. For example, a 10-hp., 60-cycle induction motor operating at about 1,800 r.p.m. has a power factor of about 90 per cent at full load and 80 per cent at half load. Either of these would be considered fairly satisfactory on most power systems. It is the low-speed motor that has a poor power factor. A 10-hp., 60-cycle motor designed to operate at 600 revolutions will have a power factor of less than 80 per cent at full load and less than 60 per cent at half load. It is evident that slow-speed induction motors are to be avoided where possible, especially if they are to operate at part load. If there is no other solution to the motor application than using a slow-speed induction motor, then some means should be provided to compensate for the power factor of the slow-speed motor.

A few years ago there may have been more or less justification for some of the induction-motor applications that were made. The synchronous motor has now been so improved and new types made available that in most applications not well adapted to induction motors the former can be satisfactorily used. In most plants, no one type will meet all the different conditions, and it is a case of selecting the type best suited to the various applications, so as to obtain the most economical arrangement. To do this requires an intelligent understanding not only of the load cycles, but also of the characteristics of the motor available for the service.

TABLE I.—POWER FACTORS OF SOME SQUIRREL-CAGE POLYPHASE INDUCTION MOTORS
(Per cent)

Rated horse-power output	Rated load, r.p.m.					
	One-half			Full		
	1,800	1,200	900	1,800	1,200	900
½	....	54	44	....	75	63
1	60	55	44	80	75	67
2	63	61	53	82	78.5	71
3	65	64	55.5	82	80	74
5	73.5	67	55	87.5	85	77
10	81	80	64	90	89.5	82
20	83	81	73	91.5	90.5	85
50	....	85	75.5	....	91.5	88

CHAPTER II

POWER FACTORS, WIRES, AND VOLTAGES

Low power factors cause reactance and resistance drops in voltage between the central station and the consumer's meter, the former being due to the magnetizing current and the latter to the total current. Low power factors, too small wires and cables, or both, are the causes of excessive resistance drops in voltage within the industrial plant between the meter and the motors, even when the voltage at the plant terminals is constant. Some causes and effects are explained herein.

11. Pressure and Flow.—In the utility's line from the central station to the consumer's meter, there is a reactance drop, due to the magnetizing current, which reduces the voltage or electric pressure at the consumer's meter. The central station sends out a supply of running current and magnetizing current for the induction motors and for other purposes. The energy of the running or working current, with the pressure from the central-station generators behind it, keeps going forward to do useful work while the energy of the magnetizing current magnetizes induction motors and other apparatus and then is exhausted back into the line. The voltage or electric pressure back of the exhaust opposes the pressure sending out useful energy to some extent. That is how the reactance drop occurs. The greater the magnetizing current the greater the reactance drop. No energy is lost, except that due to the friction of the electricity with the structures of the copper conductors, but the net pressure is reduced.

The resistance drop in pressure or voltage is the result of the conversion of a portion of the energy transmitted from the central station to the motors, and so forth, into heat due to electric resistance—a throttling effect due to the small cross-sections and relatively great lengths of the conducting wires. All electric conductors have a throttling effect on the electricity flowing in their structures; the faster the electricity flows the greater is the friction with the structure of the conductor and the greater is the electric pressure required. When the supply voltage is constant at the central station or at the consumer's meter, the additional pressure or voltage required to overcome the resistance in the conductors has to be taken from the supply voltage, with the resulting resistance drop.

From the foregoing, there may be no reactance drop right up to the consumer's meter, but there may be relatively great resistance drops in the wires and cables constituting the plant distribution system, due to their carrying currents of excessive strengths, that is, electricity flowing at too great velocities. To reduce the velocity of the electricity, make the cross-sections of the wires and cables bigger. But first look to the power factor. If the power factor can be doubled, the current strength can be halved for the same amount of power transmitted, and this reduces the resistance drop which always accompanies a loss of electric energy through its conversion into heat in the copper of the system. Think how this affects a long transmission line.

The voltage that drives the electricity in the wires to transmit electric energy through the medium of the electricity (much as a belt is the medium of transmission of mechanical energy from a driving to a driven pulley) is a pressure analogous to water (hydrostatic) pressure.

Water comes from a city reservoir through large water conductors at a good pressure when an excessive amount of water is not being used. However, when water is used extensively in an apartment house, for instance, the water pressure will be reduced somewhat in an adjoining apartment house. Aqueducts and water mains are made sufficiently large to carry the volume of water required in a given time at the required pressure or head. The water pipes in buildings obviously are smaller than the mains in the streets, and the pipes to faucets are the smallest of all. Those who have taken showers in upper apartments have noted changes in the pressure or flow of water—sometimes hot, sometimes cold—due to the use of water in other apartments. If the water pressure was the same in all apartments at all times, the same number of gallons of water per minute could be obtained from a given faucet at all times. However, such is not the case. Apartments have lowered water pressures when water is running in other apartments on the same floor. When abnormal quantities of water are being drawn all over a city, the water pressure in the various buildings throughout the city is abnormally low. If all of the mains and pipes were big enough and the capacity of the reservoir was great enough, all of the taps in a city might be opened simultaneously and there would be no noticeable drop in pressure at any tap. But such an arrangement is impracticable for many reasons.

Large flows mean reduced pressures. That is one of the problems facing utilities—how to keep the pressure up when the flow is great so as to deliver the energy on demand without notice at the time-rates required by the consumers. Like the water systems, the individual loads may be variable, but the average of all of the loads may not be so bad at the central station. However, an industrial plant having a low power factor or making abnormal demands for power without notice may seriously interfere with the operating conditions of an adjoining industrial plant due to the excessive reactance and resistance drops in the line supplying both plants.

The same general principle applies to the use of electric energy in industrial plants and the supply of this energy to the motors, lamps, and so forth, at the required time-rates. The voltage drop in the plant distribution system, caused by energy losses therein, may prove a very serious matter. Even when the wires and cables are those specified by the National Electrical Code, the number of dollars wasted annually in heating them may be sufficient to buy a new set of wires and cables each year, (Chapter X,) but a part of this waste is necessary. So far as the industrial plant is concerned, the power factor is a matter of current-carrying capacity of wires, cables, and apparatus, and the seizure of some of the electric energy by such wires, cables, and apparatus that is intended for the motors, lamps, and so forth, by converting a portion of the electric energy into heat, with the resulting loss of voltage, the slight slowing down of motors, and so forth. The smaller the current strength, the less is the heating effect which varies as the square of the current strength; 10 × 10 = 100, 100 × 100 = 10,000, and so on.

12. How a Low Power Factor Affects the Utility.—Looking at the utility's problem from the standpoint of the manufacturing-plant executive, suppose an industrial plant had two similar generators driven by two steam engines working at their full capacities, and that the plant power factor was 40 per cent. Furthermore assume that the two generators were so heated by the currents in their coils that they would burn out (insulation would be destroyed) if they carried any more load. If the plant engineer improved the plant power factor, either by juggling the

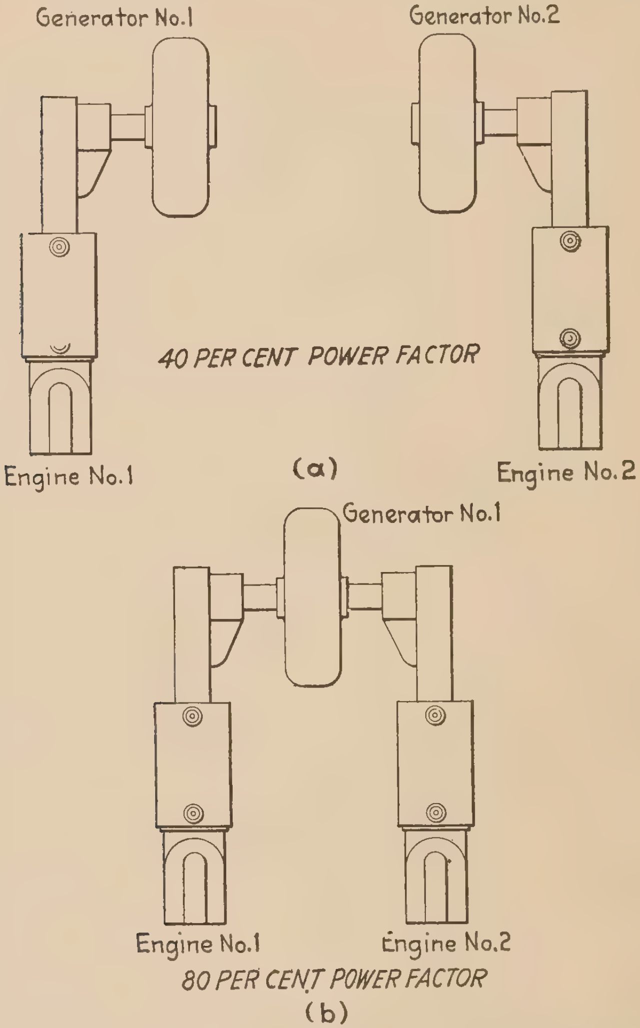

Fig. 5.—Effect of power factor on generating equipment. *a*. Two generators and two engines required for 40 per cent power-factor operation. *b*. Only one generator but both engines required for 80 per cent power-factor operation at the same load.

motors around so that most of them would be well loaded, or by using additional equipment in the form of power-factor-improving apparatus, or both, so as to obtain an 80 per cent power factor, one of the generators could be eliminated altogether and be held for emergency in case something happened to the other, or it could be otherwise employed or sold. But both engines driving the remaining generator still would be working at their full capacities, as before the generator was eliminated, and the remaining generator would become no hotter than when both generators were run with a 40 per cent power factor. More coal would stay in the coal pile, however, because the distribution losses would be reduced. If an attempt was made to carry the plant load on the remaining generator with a 40 per cent power factor, the generator would burn out in short order.

This principle applies to the sizes of all lines and electrical equipment, but the effect on the dimensions of the steam equipment is comparatively small. It is a question of current-carrying capacity *versus* the power factor, having enough electric pressure to deliver the energy at the required time-rate, and keeping the pressure constant and at its rated value right at the consumers' induction motors under all ordinary conditions. Low power factor increases the ratio of idle electrical investment to annual gross revenue, through the transmission of magnetizing current in the lines, feeders, and general electrical equipment, thus reducing the capacity thereof for conducting salable working current with the rated voltage behind it.

13. Effects of Low Power Factor in the Industrial Plant.—The manufacturing executive is interested in the maximum production, the minimum of defective products, the minimum investment in motors, starters, and wiring, the minimum power bill, the minimum maintenance cost, the minimum fuse bill, and so forth.

The speed of an induction motor varies somewhat with variations of voltage and with variations of load. When the supply voltage drops at the motor terminals, due to either the reactance or resistance drops, or both, in the utility's line and distribution system, or particularly to a combination of the above with the resistance drop in the consumers' distribution system when either the wires are too small or the power factor is too low, the motor or motors slow down somewhat, particularly underload and when the load comes on as the voltage drops. While the voltage variations do not, as a general rule, greatly affect the speeds of induction motors, they do affect the production and the number of defects. Hence, in many cases the unit cost of the product is reduced through the smoother running of machines when the power factors of the motors are suitably corrected.

The filaments of incandescent lamps are purposely made small and of such material that they require all of the rated voltage to push the electricity in their structures at such velocities as to heat them to such extents that they give off light of the proper intensity. When the voltage at the lamps is less than the rated voltage, they give off less light and operate at lower efficiencies. The power factor of an incandescent lamp is substantially 100 per cent, or unity. Consequently, lamps loads and resistance heating loads, in general, help to increase the plant power factor.

Induction motors may require at least double the current to start them that is required to run them when they are started with the full load connected, but this ratio often is much greater. For instance, W. A. Layman states in Art. 35:

> Is it not a principle that could and should be established that the central union cannot permit the magnetizing current to interfere with good service to adjacent customers? It seems that if it is logical to rule off heavy starting currents which temporarily disturb good regulation of the system, it is equally logical to rule off heavy magnetizing currents which continually impair good regulation.

Therefore, when the wiring is too small or the power factor is too low, the voltage in the distribution system is reduced when large induction motors are started, and the voltage varies when the loads on motors and other electrical apparatus vary. Somewhat like incandescent lamps, induction motors are very sensitive to voltage variations. The starting and stopping of motors driving elevators, the variations in loads on motors driving compressors, and so forth, cause variations in the voltage at the terminals of other motors unless the wiring is of proper size and the power factor is suitable. Thus the starting of one motor, or the variations in the loads of some other motors, affect the speeds of the motors and the machines they drive in proportion to the sizes of conductors used and the magnitude of the power factor. The worst effects are due to variations in voltage at the meter. This also causes the light from the lamps to vary. It may be produced by a neighboring industrial plant where intermittent but great demands for power are made by large motors driving compressors and the like, especially when the neighboring plant has a low power factor, because then the reactance drop may be relatively great.

Where two-charge rates prevail, the utility makes an additional charge for the demand made upon it without notice by the latter kind of a plant, for instance, and sometimes imposes a penalty for power factors less than a given value. A consumer with a good inherent power factor, however, may be penalized by such a neighbor through the cost imposed upon the former by the latter's demand.

Reduced speeds, the blowing of fuses, and lessened illumination lower production. Actual gains of 10 per cent and more in production have been achieved by improving the power factor, mostly due to the smoother running of machines.

Variable speeds and variable illumination contribute to inferior products. A reduction in defects generally is reported where the power factor has been improved.

The minimum investment in motors, starters, and wiring is obtained by using motors only large enough for the drives, thus tending to keep the power factor high.

The minimum power bill depends upon many factors, but the saving may amount to half a cent per kilowatt-hour as billed.

The maintenance cost is lowest where there is the least and smallest apparatus to maintain.

Smaller fuses are used after power-factor improvement because the current strength has thus been reduced, but this particularly applies to correction at the motor or near the motor terminals. Furthermore, fuses do not blow so often when motors are running at approximately constant speeds and constant voltage.

In an industrial plant where the motors and machinery hum at constant speeds, and where proper illumination gives good, steady light, there is sure to be found a healthy psychology among the workers.

14. Saving in Distribution by Increasing the Power Factors of Motors.—If an induction motor having an inherent power factor of 80 per cent at one-half the full-rated-load output should become so underloaded that its power factor was only 40 per cent, then the motor would be drawing double the current per horsepower output that would be required when operating at one-half the full rated load. By substituting a smaller motor therefor, the load could be carried thereby with a power factor of 80 per cent or more if the load was constant.

Doubling the power factor at an induction-motor position, as from 40 to 80 per cent, by the use of a smaller motor or by power-factor-corrective apparatus and without changing the load, reduces the current strength in the wires leading to it and also within it (when a smaller motor is used, but not when power-factor-corrective apparatus is employed) by 50 per cent—that is, the current strength is halved—and also reduces the heating to only 25 per cent—that is, to one-quarter of the original heating at the low power factor of 40 per cent. Looking at the matter from another angle, if the power factor is 80 per cent and a larger motor is installed so that the power factor falls to 40 per cent with the same load, the current strength will be doubled and the heating of the wires will be four times greater than what it was when the power factor was 80 per cent at the same load. So the *excess* of heating of wires will be three times what the *total* heating would be if the power factor was 80 per cent. Where power-factor-improving apparatus is installed in connection with low-power-factor motors, as when the load is exceedingly variable, a saving of at least 85 per cent of the energy previously wasted in heating wires and apparatus external to the motor may result.

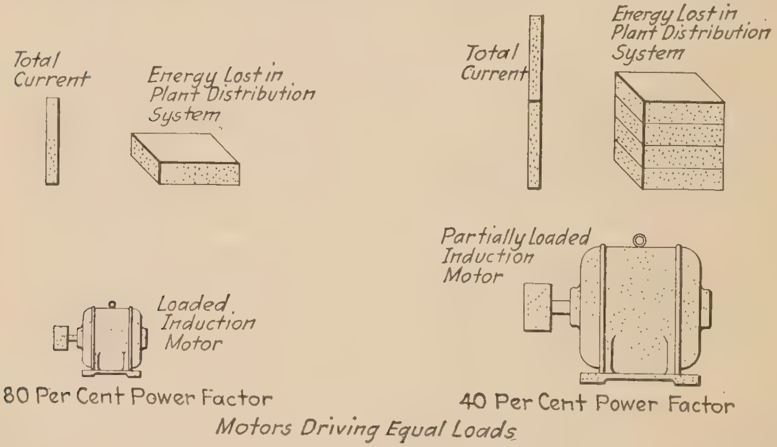
Total Current
Energy Lost in Plant Distribution System
Loaded Induction Motor
80 Per Cent Power Factor
Total Current
Energy Lost in Plant Distribution System
Partially loaded Induction Motor
40 Per Cent Power Factor
Motors Driving Equal Loads

FIG. 6.—Relative energy losses in distribution system with two different sizes of induction motors carrying equal loads. The smaller motor has an efficiency about equal to that of the large motor, but has a power factor double that of the larger motor and, therefore, causes but one-quarter of the energy loss in the distribution system caused by the use of the larger motor for the same load.

Therefore, correcting a low power factor within the industrial plant necessitates the economic choice of loading induction motors already installed or substituting smaller motors therefor, increasing the sizes of the wires, cables, and so forth, in the distribution system, installing power-factor-improving apparatus, or combining at least two of these items.

Power-factor-improving apparatus does not "correct" the power factor of an induction motor. Neither does it decrease the total current strength in the motor. It corrects the power factor of the induction motor and the power-factor-improving apparatus combined as a unit, but it does not decrease the total current strength in the wires at and within the motor, or in those connecting the motor to the power-factor-improving apparatus. The power factor of a static condenser, for instance, is very small, as it should be.

The sizes of wires and cables in the plant distribution system should be so related to the power factor that the cross-sections of the copper conductors will be such that the annual cost of the energy wasted in the form of heat is equal to that portion of the capital invested in the distribution system which can be considered proportional to the weight of copper used, Art. 56. This shows that the money lost in an existing system as the current strength increases varies directly with the current strength. But there is also the National Electrical Code to be considered. The cheapest way, in many cases, is to leave the distribution system alone and make the power factor what it should be. Even then, however, the load may have been so increased since the original installation of the distribution system by the addition of motor and other loads that the plant distribution system, or portions of it, may require more copper. Power-factor-corrective devices installed at or near induction motors or other inductive apparatus reduce the current strength and heat losses in plant distribution systems, but they do not increase the sizes of the copper wires and cables so that they will carry overloads economically. When such power-factor-corrective methods fail to relieve the distribution system, the latter must be reenforced or the plant voltage must be increased. Raising the plant voltage has the same effect as increasing the power factor, so far as the plant distribution system is concerned. Changing from 220 to 440 volts halves the current strength and quarters the energy lost in heat.

Power factor, cross-section of copper, and plant voltage all are intimately associated in the plant distribution system.

CHAPTER III

IMPORTANCE OF KEEPING MOTORS LOADED

Idle or underloaded motors may prove a big item of expense. Some makes of induction motors are guaranteed to run at the full rated load continuously for 24 hours without the temperature rise exceeding 40°C. and, in addition, they are guaranteed to carry 25 per cent overload for two hours without the temperature rise exceeding 55°C. Whenever one motor can do the work of two underloaded motors, the power factor is improved and other obvious savings are made. The subject is discussed in the present chapter, along with the importance of connecting power-factor-corrective apparatus close to the induction motors.

15. Load Factor.—Too great an investment in unnecessary equipment may prove a large waste. The fixed charges of a plant consist of the investment and replacements. Interest and taxes carry the investment, while insurance and depreciation funds cover the replacements.

In electrical consumption, the plant load factor is the percentage of full-load capacity of the entire plant being used. Thus, if the plant load factor is 50 per cent, the net result, so far as the load is concerned, is as though only one-half of the plant was operating at full load and the other half was lying idle. But the investment of the entire plant has to be carried just the same, and the half that is operating at full load has to carry both its share of the investment and that of the other half lying idle.

Thus, 100 minus the load factor indicates the percentage of time that the whole plant may be considered as lying idle. Since interest and taxes must be paid on the investment whether or not the plant is operating, it is desirable to maintain the load factor at as high a value as may be found practicable.

There is a close relationship between the load factor and the power factor of an induction motor. Some efficiency and power-factor curves of various induction motors are shown in Figs. 39 and 40, Chap. VIII. It will be noted that the power factor varies with the load factor more than does the efficiency, but the latter also must be considered because the efficiency determines the actual power consumed by the motor at a given load with respect to its useful output.

The load factor of a motor is the ratio of the average power input to the full-rated-load power input.

The weighted sum of the load factors of all of the motors in operation in a plant at any given time is equal to the plant load factor at that time.

Increasing the load factor of an induction motor from 50 to 100 per cent increases the power factor about as shown in Table I, Chap. I and halves the investment in motors and their starters if all motors have their load factors similarly increased and can be loaded, or if one-half of the motors could be removed so that the remaining half would be fully loaded, providing that the value of the motors removed was equal to the value of the remaining motors. Motors cannot often be operated, however, at 100 per cent load factor, although they may in some cases.

The load factor approaches 85 per cent as a practical maximum. The load factor for compressor operation, which, of course, is intermittent, may be taken as 60 per cent as an average value.

The load factor shows whether the plant is properly motored. The plant load factor is determined from the monthly bills. The plant power factor is often given on the monthly bills.

To improve the load factor and simultaneously improve the power factor, a survey may be made if the engineer making it has had sufficient experience. Otherwise, tests of the motors (5-hp. and larger in large plants) must be made. This test is necessary in all cases of doubt as to the condition of the motor, as whether it is old and has bad iron or whether it has been repaired, and so forth. If the load factor can be increased by recommendations based on a survey, the expense of an actual test can largely be eliminated, and the money thus saved may be applied to labor charges for changing motors and storing those not needed, which may be used for replacements as occasion requires, or for power-factor-corrective apparatus.

16. Investment in Motors.—The relative investment is dependent upon the load factor and also upon the power factor. In a plant having, say, an investment of $12,000 in induction motors that are loafing and turning out about what $6,000 worth of motors might do, there is $6,000 too much invested in motors. While this may be a rather extreme case, it is used for illustrative purposes. The removal of $6,000 worth of motors in such a case, with conditions favorable for making the remaining $6,000 worth of motors drive the machinery in a proper manner, would give somewhat greater and better production at a higher power factor. It must be remembered, however, that 1,800-r.p.m. motors alone may cost about as follows, as listed:

3-hp	$25 per horsepower
5-hp	$16 per horsepower
10-hp	$14 per horsepower
15-hp	$12 per horsepower
20-hp	$10 per horsepower
30-hp	$9 per horsepower

Some of the benefits directly obtained by increasing the load factor without increasing the load are:

1. Increased power factor and all of the benefits that go with it.

2. Usually there is less equipment in use after correcting the load factor, because drives may be combined and made flexible so that many motors and their starters may be eliminated altogether.

3. There are almost always a number of large motors removed which may have greater money values than those which replace them, because drives may be combined and made flexible so that many motors may be eliminated altogether and may be sold for about 40 per cent of their original cost or may be placed in stock for future drives. Such motors are always handy for emergency drives while other motors are being repaired.

4. The removal of motors means less maintenance smaller and less expensive starters, fuses, and so forth.

5. Much shafting, hangers, and belting are usually salvaged by correctly changing motors, and these may be placed in stock for new drives.

To cite a single instance[1] within the author's experience in consulting work, refer to Fig. 7 which shows a 15-hp., six-pole, squirrel-cage, three-phase induction motor driving rolling barrels, a blower, and a centrifugal separator, through a 90-in. steel pulley.

The drive formerly consisted of a floor-mounted, 30-hp., eight-pole, three-phase induction motor. Tests of this motor showed the average power input to be 11 kw. with a peak of 12.5

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[1] UNDERHILL, C. R., "Improving the Power Factor," *Power*, vol. 62, p. 456, 1925. (Winner of *Power's* first cash prize for "Practical Ideas from Practical Men," September, 1925.)

kw. when everything was running. The power factor averaged about 63 per cent.

The 15-hp. motor was one of a number of motors released while changing motors around and loading them up to increase the plant power factor above the penalty point without purchasing any power-factor-corrective apparatus, which was successfully accomplished, and the 30-hp. motor was required for a new drive. Hence, the only cost was for labor in changing the positions of the motors, except the pulley, which was saved from the alligator shears at a cost of $60, and the belt used in the drive; and the following material was recovered from the former 30-hp. drive: two jackshafts, four large hangers, one 14-in. pulley, one 18-in. pulley, two 34-in. pulleys, a 35-ft. single 7-in. belt, a 30-ft. single 10-in. belt, and a 20-ft. double 10-in. belt.

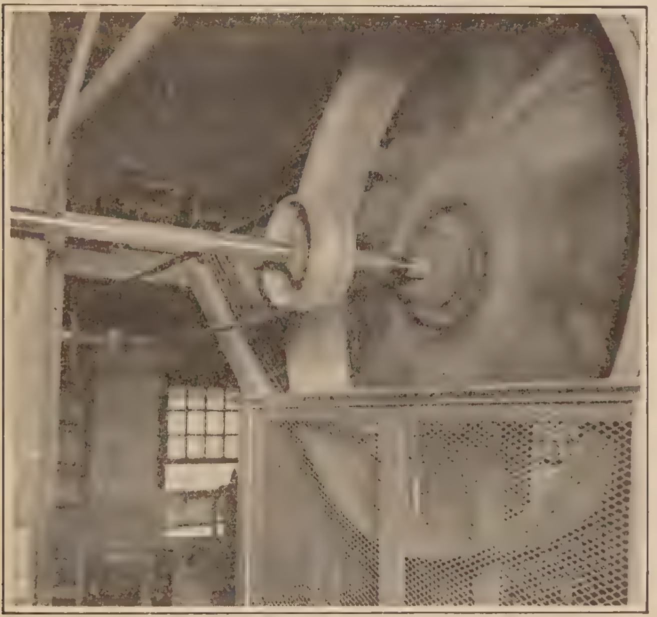

FIG. 7.—Arrangement of the new drive.

The belts were cleaned, dressed, and placed in stock for other jobs, in accordance with the program adopted, and no belts had been purchased for this particular plant for over six months (up to the date of the article) excepting in a few instances.

As shown in the illustration, the center to center distance between the motor and the mainshaft is 9 ft. and the speed of the motor is about 1,150 r.p.m. This drive is made possible by the use of a special belt with an oak leather backing having strips of chrome leather, saturated with tallow, riveted thereto. The drive is quiet in operation, and not one case of trouble has been reported up to this time of writing.

The foregoing emphasizes the importance of substituting motors where practicable before installing power-factor-corrective apparatus. If such apparatus had been installed in the present case and no changes in motors had been made, the extra friction load and the unnecessary material causing it would not have been eliminated and a new 30-hp. motor would have been purchased for the new drive.

Where induction motors are employed, the plant load factor is related to the plant power factor in such a manner that when the plant load factor goes up, the plant power factor also is improved. This is natural, since loading the motors improves the power factor. Plant load factors averaging 65 per cent or more may be obtained. The author seldom has seen an excessively overloaded induction motor, that is, one that the electricians allowed to run so hot as to burn out due to overload. Some electricians have a habit of watching out for hot motors, and if a motor is cool while running, they are apt to think it quite satisfactory. Burnouts are usually due to low voltage, water or oil getting into the coils, or to worn bearings which permit the rotating part (the rotor) to rub against the stationary part (the stator) through the negligence of those responsible for regularly inspecting the motors. The purchasing department will supply sets of feelers to maintenance men for gaging the distance between the rotor and the stator of each motor at various points.

17. Mistaken Ideas Regarding Motors and Their Loads.— Some electricians and foremen want unnecessarily large motors. They have notions that when the belt slips off in starting, the motor is not large enough. Burnouts due to causes similar to those above mentioned also are the causes of requests for larger motors. The factor of safety so frequently referred to is often an absurd reason for using motors entirely too large for the drives assigned them. Using the wrong taps on compensators for starting induction motors is another reason for thinking the motor not large enough. Another wrong impression is that large, low-speed lathes require much more power than do smaller high-speed lathes. Sometimes, large motors are placed in new locations and are connected in branches with other motors. In such cases, the larger motors will not start well because of the resistance drop. More copper at least in the branches is the answer in such a case.

Within the author's experience, great protests have been made when two separate loads respectively driven by, say, a 15-hp. and a 10-hp. induction motor were combined as a single drive and the 10-hp. motor eliminated, leaving the 15-hp. motor to do all the work. Motors recommended for removal so as to be replaced by smaller and more suitable ones have had weird tales told regarding them by foremen—how fire shoots out from them while running—while tests proved them to be underloaded but otherwise O. K., and when placed on new drives giving them greater loads, no trouble of any kind was reported. The slowing down of motors somewhat is another reason for thinking them overloaded, although motors do slow down under such circumstances, when the real reason has been found to be low voltage and load combined. Some shop men cannot understand how the useful load on a three-quarter-loaded motor can be doubled without burning out the motor. The answer is that the friction load constitutes one-half of the full rated load in such cases, and so the useful work is only one-quarter of the full rated load. Hence, it can be (and often has been) doubled.

The fact that a fuse in one of the phases of a three-phase motor circuit often blows without stopping the motor, which then runs on single phase and which is not detected until the following morning when the motor will not start, is a proof that such induction motors are underloaded. It further shows that induction motors may run with badly unbalanced phases. The maximum output of a three-phase induction running single phase is about 40 per cent of that when the motor is running three phase. The author's practice is to test induction motors up to 50-hp. while running by letting them run single phase while inserting current transformers. The percentage of cases where the motors have tended to slow down on single phase, thus indicating a good load, has been exceedingly small.

H. L. Cape, Birmingham, England, writes as follows to the editor of *Electrical World:*[1]

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[1] Vol. 86, p. 699, 1925.

Judging by the amount of attention given to the power factor in the *Electrical World*, it would appear that plant engineers in America are more alive to this subject than the majority of plant men in this country. I have always agreed with the view expressed in the article of P. C. Jones, which appears on the same page as Mr. Fynn's letter, *viz.*, that ordinary induction motors should be worked high up on the load curve, assuming, of course, that a good general compromise is made.

In this connection I have in mind a certain large industrial plant working with a great number of three-phase induction motors where the conditions for almost constant load are very favorable. In this plant most of the machines are only lightly loaded. The plant engineer, on being questioned about the great number of unnecessary machines, made the statement that it made the power factor high—in many cases over 100 per cent.

It is no exaggeration, I think, to say that the statement given above would represent the type of "knowledge" which a fair proportion of responsible plant men in this country possess—a fact to be regretted.

If the bare hand can be held on the stator iron of an induction motor for a minute or more at the completion of a day's run, the motor has not been overloaded on the average. This practical test should be made several times during the day where there is any doubt, and as a final measure, complete tests should be made. A cool induction motor should be looked upon with profound suspicion and with a view to replacing it with a smaller motor of about the same efficiency after its case has had due consideration. When a motor overheats on an average power input less than the full-rated-load value, as measured over relatively short-time intervals, there is something the matter with the motor and it is not too small for the drive. An induction motor will carry a load equal to two and a half times its full-rated-load power input for brief periods without injury and without stopping, although the speed will be reduced on such heavy overloads even at full impressed voltage. The limit to the constant load on a running induction motor is the maximum temperature that will not impair its insulation.

18. Motors and Power-factor-corrective Apparatus.—Why load the induction motors before connecting power-factor-corrective apparatus to them when such loading is practicable? To increase the load factor and thus eliminate motors that are not needed so that they may be put on new drives or sold, and also to save the cost of the additional power-factor-corrective apparatus which would be needed should the motors be allowed to run underloaded. But after the motors have been properly loaded as well as conditions, including cost, will permit, then savings may be effected with suitable forms of power-factor-corrective apparatus. As an example, the power factor of a certain half-loaded, 15-hp., squirrel-cage, polyphase induction motor is 76 per cent. Since the motor is only half loaded, the load factor is only 50 per cent. This half load may be taken as an average load; 76 per cent is not a very bad power factor. The full-rated-load power factor of the same motor is 90 per cent.

By way of further explanation, if the power factor of the half-loaded motor had been increased from 76 to 90 per cent by means of a static condenser or other power-factor-corrective apparatus costing X dollars, without increasing the load factor of the motor above 50 per cent, there would be no improvement in the load factor, and a motor too big for the job would still be used. If the load carried by a 7½-hp. motor was added to that already driven by the 15-hp. motor, so as to make the horsepower output 15 hp., for which the motor was designed and at which it is rated, the 7½-hp. motor would be released, the power factor automatically would jump to about 90 per cent, and the load factor to 100 per cent. If the 15-hp. motor was removed and a 7½ hp. motor was put in its place, so as to drive only the load of 7½ hp., the power factor would be in the neighborhood of 88 per cent and the load factor would average 100 per cent.

If the 15-hp. motor had been loaded and thus had caused the power factor thereof to rise to about 90 per cent and the load factor to 100 per cent, and had simultaneously saved an investment of X dollars in power-factor-corrective apparatus, a 7½-hp. motor having a list price of about $200 complete would be released; so the total saving on this basis would be $200 plus X dollars (less the cost of changing motors).

If the 15-hp. motor was replaced by a 7½ hp. motor, without using any power-factor-corrective apparatus, about $60 (the difference in the cost of the motors) would be gained, so that a saving of about $60 plus X dollars would be made (minus the cost of changing motors).

Induction motors have inherent or natural power-factor-improving characteristics due to the increasing ratio of the running current to the total current as the load factor increases. Hence, the power factor increases with the load.

External power-factor-corrective capacity is often required to effect further savings even after the motors have been loaded as much as practicable.

The relation of the inherent to the external power-factor-improving capacity required for squirrel-cage, polyphase induction motors of 5-hp. or greater rating is as follows:

1. The power-factor-improving capacity required to increase the half-load power factor of an induction motor to the full-rated-load power factor is approximately equal to that required to improve the full-rated-load power factor of the same motor to about 96 per cent.

2. The power-factor-improving capacity required to increase the half-load power factor of an induction motor to its full-rated-load power factor may be supplied by the motor if it can be kept fully loaded (100 per cent load factor).

3. The power-factor-improving capacity required to increase the full-rated-load power factor of an induction motor to any higher power factor, without overloading the motor, must be supplied by external means, as by a static condenser.

4. The external power-factor-improving capacity, as in static condensers, required to increase the half-load power factor of an induction motor to about 96 per cent, without increasing the load factor of 50 per cent, is approximately double that required to increase the half-load power factor of the same motor to its full-rated-load power factor by simply loading the motor so that its load factor shall increase from 50 to 100 per cent.

In the above, "half-load" refers to 50 per cent load factor, while "full-rated-load" refers to 100 per cent load factor.

Why use external power-factor-corrective apparatus at all? Because induction motors cannot always be operated at or near their full rated loads, on the average, when there is said to be a diversity of operation—the wider the range of load the greater the diversity of operation. This is the case in rolling-mill and calender drives where the larger sizes of motors are employed, but especially in the textile industry where small individual drives are used.

19. Keeping Power-factor-correcting Apparatus Close to the Motors.—Why not connect a large condenser of some sort directly across the plant terminals or at the load center, as at the meter, and let it take care of all of the motors? When this is done, it keeps the magnetizing current out of the utility's lines and equipment only, but not out of the consumer's wires and equipment. Thus, while it improves the voltage regulation and reduces or eliminates any power-factor penalty or earns a bonus where such clauses are in the rate schedules and are enforced, or offered, it does not reduce the heat losses and corresponding voltage drops within the consumer's plant, with the resulting costs heretofore discussed.

The above statement also holds true to a certain extent where such devices are connected at various places throughout an industrial plant to improve the power factors of groups of motors, although often it is necessary to do so where small motors, as fractional-horsepower motors, are used, and also in other cases.

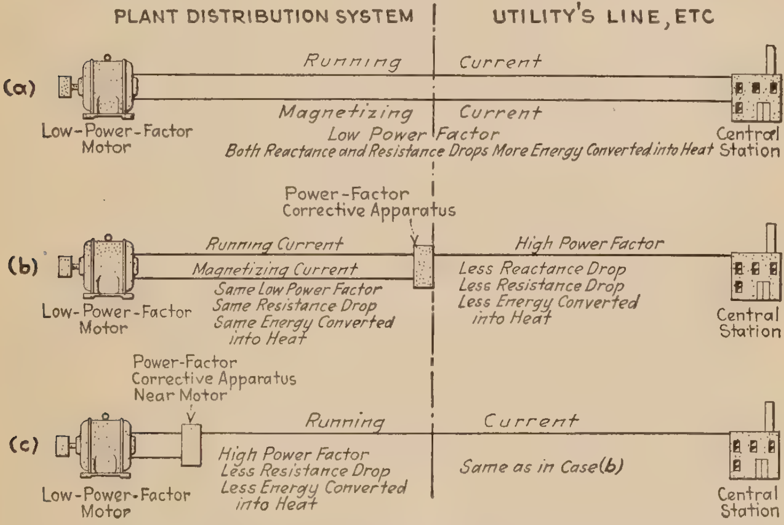

FIG. 8.—Various stages of power-factor correction. Substation correction not included. *a*. No power-factor correction. *b*. Correction at plant terminals or load center. *c*. Correction near motors.

All of the above power-factor-improving devices are useful in other fields. The point of this argument is that the closer any form of power-factor-improving apparatus is placed to the induction motors producing the low power factor, the less will be the magnetizing current in the wires, cables, and other electrical equipment from the motor terminals (where the low power factor is produced) clear back to the meter or plant terminals.

There are cases where unity-power-factor or synchronous motors may replace induction motors, and certain high-power-factor motors have recently been developed. The Fynn-Weichsel motor may be used to good advantage in replacing induction motors and simultaneously supplying magnetizing current, when connected close to a low-power-factor induction motor or other device, or near a group of small motors, and in other instances, because it not only runs at an inherently high power factor but simultaneously improves the power factors of nearby motors.

The author's position in the above matter was given in a discussion of a paper[1] by H. Weichsel, to which he replied as follows:

> Mr. Underhill recommends improving the power factor in an installation by properly selecting the size of the induction motors in respect to the load which they have to carry. There is no doubt that by this method a very great improvement in the power factor of the system can be obtained. I like to call attention, however, to some of its limitations. Many industries exist in which the load on the machinery is seasonal, and in such cases it is not advisable to change the capacity of the motors in accordance with seasonable business of the industry. There are also many cases where motors must carry, for a relatively short time, heavy loads and, for great periods of time, operate at no load or fractional load. Frequently, the capacity of a squirrel-cage motor is governed rather by the starting requirements than by the running load.
>
> These conditions can be particularly well cared for by installing machines which operate at unity or leading power factor for most of the time as described in the paper. Installations of this kind also overcome the difficulty which Mr. Underhill pointed out that heavy leading currents exist in wiring in such cases where the power-factor correction is obtained by centralized power-factor-correcting devices, such as synchronous condensers or static condensers.

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[1] "A New Alternating-current General-purpose Motor," *Journal*, A. I. E. E., vol. 44, p. 356, 1925.

CHAPTER IV

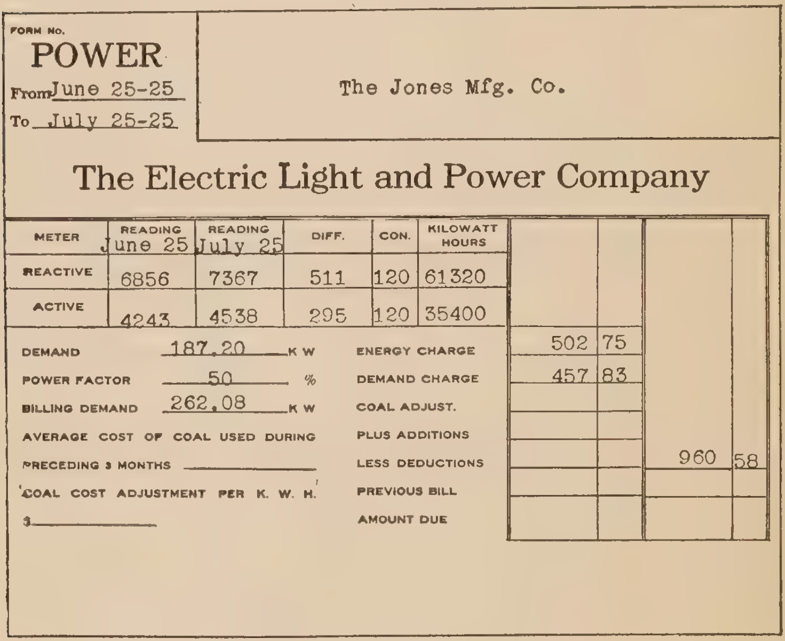
ANALYSES OF POWER BILLS

There are many kinds of rate schedules and many forms of power bills. In the form of rate schedule and bill herein discussed, it is possible, by simple analysis, to discover unusual occurrences within the consumer's plant that otherwise might pass unnoted. Electric energy and power, the demand, and the effect of the power factor on the demand are discussed in detail. Then follow the method of finding the plant load factor, and some suggestions.

20. The Power Bill.—On or about the first of each month, the power user receives a bill from the electric light and power company. The bill in Fig. 9 is a facsimile of one form based on a two-charge rate. There is one charge for the *energy* consumed, which directly includes the energy wasted in heating the wires and equipment belonging to the power user, and another charge for returns on the investment in extra electrical equipment installed by the utility to supply the *demand* made upon it without notice by the consumer's motors, electric furnaces, electric ovens, lamps, and so forth.

The sum of the two charges, with coal adjustments and any additions, is the amount of the power bill. The ratio of the energy charge to the demand charge represents, in a general way, the profit to the utility. The utility strives to increase the energy consumption, as through new business and loads, and, in certain cases, to decrease the demand. A low power factor increases the demand by tying up electrical equipment that would handle more power if the coils were not heated by the increased total current. The energy charge may be reduced by adjusting the size of the plant distribution system to the total current, and *vice versa,* and by reducing the friction load when possible or practicable. The demand charge may be reduced by increasing the power factor, as hereinafter shown, and by studying the causes of peaks in the plant load at various times throughout a given time interval.

In the case of the bill in Fig. 9, there is a power-factor penalty for all average power factors less than 0.70, or 70 per cent, as measured over the preceding month. The measured demand is the greatest amount of power in kilowatts (kw.)[1] demanded by the various components making up the plant load, including the distribution system, as measured over continually succeeding 15-min. intervals throughout the entire preceding month. The measured demand, therefore, is the greatest average amount of power in kilowatts demanded during any 15-min. interval during that month.



FORM NO.

POWER

From June 25-25

To July 25-25

The Jones Mfg. Co.

The Electric Light and Power Company

METER	READING June 25	READING July 25	DIFF.	CON.	KILOWATT HOURS
REACTIVE	6856	7367	511	120	61320
ACTIVE	4243	4538	295	120	35400

DEMAND 187.20 K W

POWER FACTOR 50 %

BILLING DEMAND 262.08 K W

AVERAGE COST OF COAL USED DURING PRECEDING 3 MONTHS ____

COAL COST ADJUSTMENT PER K. W. H.

$ ____

ENERGY CHARGE	502	75		
DEMAND CHARGE	457	83		
COAL ADJUST.				
PLUS ADDITIONS				
LESS DEDUCTIONS			960	58
PREVIOUS BILL				
AMOUNT DUE				

Fig. 9.—Power bill with power-factor penalty.

In Fig. 9, the power factor is 50 per cent and the measured demand is 187.20 kw. Since a low power factor makes an additional demand on the current-carrying capacity of the utility's lines and equipment, thereby necessitating more copper and equipment than otherwise would be needed, as well as an additional power demand thereon, the demand for billing purposes is increased by $(^{70}/_{50}) - 1 = 1.40 - 1 = 0.40$, or 40 per cent, more than the actual measured demand, making the billing demand equal to 187.20 kw. × 1.40 = 262.08 kw., the increase of 262.08 kw. − 187.20 kw. = 74.88 kw. (which is 40 per cent of 187.20 kw.) in the billing demand, over that of the measured demand, being due to the low power factor of 50 per cent. Divide the specified lowest power factor by the measured average power factor and multiply the quotient by the measured demand. The product is the billing demand.

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[1] 1 kw. = 1,000 watts = 1.341 (about 1⅓) electrical hp. 1 electrical hp. = 0.746 (about ¾) kw.

In the contract on which the bill in Fig. 9 is based, the demand charge is determined as in Table II.

TABLE II.—DEMAND CHARGE

Amount, kilowatts of demand	Rate per kilowatt per month	Resulting charge
First 5	$3.50	5 kw. $ 17.50
Any part of next 10	2.75	15 kw. 45.00
Any part of next 35	2.10	50 kw. 118.50
Any part of next 250	1.60	300 kw. 518.50
All in excess of 300	1.25	

Since the billing demand in Fig. 9 is 262.08 kw., due to the 50 per cent power factor, the demand charge therein is computed as follows:

50 kw	$118.50	
262.08 kw. − 50 kw. = 212.08 kw.		
212.08 kw. at $1.60 per month	339.33	
Demand charge		$457.83

The demand charge is for a 15-min. job once per month. The demand meter records the greatest average consumption of power in kilowatts during each successive 15 min., day and night, for the whole month. The highest of all of the recorded average kilowatts during any 15-min. period in the whole month is the measured demand given in the power bill in Fig. 9. The demand meter may show 100 kw. as the greatest average demand during some 15-min. period in one day and 150 kw. as the greatest average demand for some 15-min. period on some other day, but that little 15-min. job on some particular day determines the 187.20-kw. demand in Fig. 9 on which the demand charge, with or without the power-factor penalty, is based. Hence, it is well to watch the demand meter and try to hold down the demand by ascertaining its cause. Perhaps too many motors produce peaks simultaneously, or normally engine-driven generator loads are switched over to the utility's line before the load has fallen off at noon or at night.

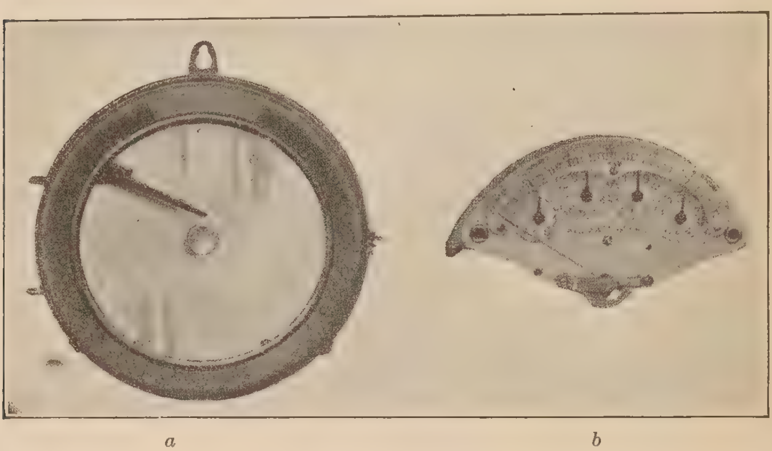


Fig. 10.—G. E. demand meters. *a.* Graphic type. *b.* Indicating type for use in watt-hour meters.

The energy charge is determined as in Table III.

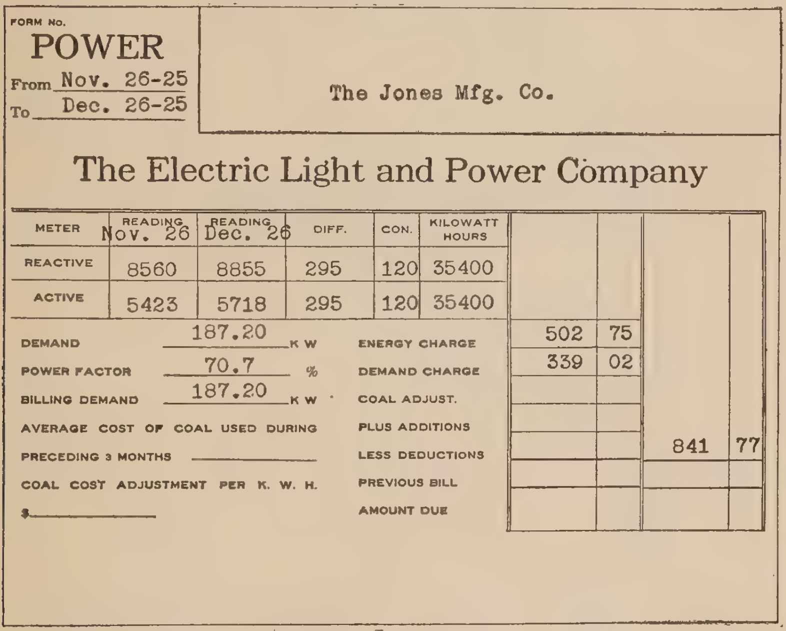
Table III.—Energy Charge

Amount, kilowatt-hours per month	Rate per kilowatt-hour, cents	Resulting charge	
First 500	4.0	500 kw.-hr. $	20.00
Any part of next 1,000	2.5	1,500 kw.-hr.	45.00
Any part of next 8,500	1.65	10,000 kw.-hr.	185.25
Any part of next 40,000	1.25	50,000 kw.-hr.	685.25
Any part of next 100,000	1.0	150,000 kw.-hr.	1,685.25
All in excess of 150,000	0.9		

In the power bill in Fig. 9, the charge for the number of active kilowatt-hours, which is the energy actually consumed, is computed as follows:

10,000 kw.-hr.	$185.25	
35,400 kw.-hr. − 10,000 kw.-hr. = 25,400 kw.-hr.		
25,400 kw.-hr. at 1.25 cts. per kilowatt-hour	317.50	
Energy charge		$502.75

The total amount of the bill in Fig. 9 is the sum of the demand and energy charges, or $457.83 + $502.75 = $960.58, and this is the amount to be paid. The actual amount paid per kilowatt-hour on the above basis is equal to $\dfrac{\$960.58}{35{,}400 \text{ kw.-hr.}} = 2.71$ cts.



FORM No.

POWER

From Nov. 26-25

To Dec. 26-25

The Jones Mfg. Co.

The Electric Light and Power Company

METER	READING Nov. 26	READING Dec. 26	DIFF.	CON.	KILOWATT HOURS
REACTIVE	8560	8855	295	120	35400
ACTIVE	5423	5718	295	120	35400

DEMAND 187.20 K W

POWER FACTOR 70.7 %

BILLING DEMAND 187.20 K W

AVERAGE COST OF COAL USED DURING PRECEDING 3 MONTHS ____

COAL COST ADJUSTMENT PER K. W. H.

$____

ENERGY CHARGE	502	75		
DEMAND CHARGE	339	02		
COAL ADJUST.				
PLUS ADDITIONS				
LESS DEDUCTIONS			841	77
PREVIOUS BILL				
AMOUNT DUE				

Fig. 11.—Power bill without power-factor penalty.

If, for any reason, as by properly loading the induction motors or by installing power-factor-corrective apparatus, the plant power factor is increased to 70 per cent or more, the bill for the same amount of energy in kilowatt-hours and the same measured demand in kilowatts would be as in Fig. 11, the demand charge being computed as follows:

50 kw.	$118.50	
187.20 kw. − 50 kw. = 137.20 kw.		
137.20 kw. at $1.60 per kilowatt per month	220.52	
Demand charge		$339.02

The total amount of the bill in Fig. 11 is the sum of the demand and energy charges, or $339.02 + $502.75 = $841.77. The actual amount to be paid per kilowatt-hour in this case, with a 70 per cent power factor, is equal to $\frac{\$841.77}{35{,}400 \text{ kw.-hr.}} = 2.38$ cts. instead of 2.71 cts., with the 50 per cent power factor, which is one-third cent more per kilowatt-hour.

The saving per month when the power factor is 70 per cent (or greater) over the amount billed when the power factor is 50 per cent is the difference between the demand charges in Figs. 9 and 11, since the energy charges are the same in both cases, and this is equal to $457.83 − $339.02 = $118.81, or about the same as the demand charge for the first 50 kw.

A saving of $118.81 per month is the equivalent of a saving of $118.81 × 12 = $1,425.72 per *annum*, and this saving can pay for the correction of the power factor. Yet it is only one of the savings due to increasing the power factor—only from 50 to 70 per cent in this case.

The foregoing is but one example of the various cases that might be mentioned, but it is given merely to show the principle in this particular case. It is no criterion, as will be readily understood further on.

21. How the Data for Above Power Bills Are Obtained.—In a balanced three-phase system, the electric power may be taken as equal to 0.001 73 times the continued product of (1) the voltage in volts as indicated by a voltmeter, (2) the current strength in amperes as indicated by an ammeter, and (3) the power factor as indicated by a power-factor meter—all at the same instant. Usually, it is indicated by a kilowatt meter.

The demand meter of the type above described operates in conjunction with the kilowatt-hour meter and leaves a record of the demand over every succeeding 15-min. interval during a given period, as one week. When a three-phase system, for instance, is unbalanced, that is, when there is a greater load connected across any two of the three wires than across any other two, it is difficult accurately to determine the power factor except as described below.

In the type of bill in Figs. 9 and 11, the number of reactive kilowatt-hours is taken from a reactive kilowatt-hour meter and the number of active (or working) kilowatt-hours is taken from an active kilowatt-hour meter. The average power factor for the month is then computed by taking the square root of the sum of the squares of the active and reactive kilowatt-hours and dividing the number of active kilowatt-hours by the square root thus obtained. For instance, in the bill in Fig. 11, the difference in the readings of the respective two kilowatt-hour meters for one month is multiplied by the constant 120 (which is the common constant for both instruments) to obtain the number of reactive kilowatt-hours and the number of active kilowatt-hours, respectively, for that month. The square of the number of reactive kilowatt-hours is 3,760,142,400 and the square of the number of active kilowatt-hours is 1,253,160,000. The sum of the squares of the two quantities is 5,013,302,400, and the square root of this quantity is 70,800. Dividing the number of active kilowatt-hours by 70,800 gives $\frac{35,400}{70,800} = 0.50$, or 50 per cent, as the aver-

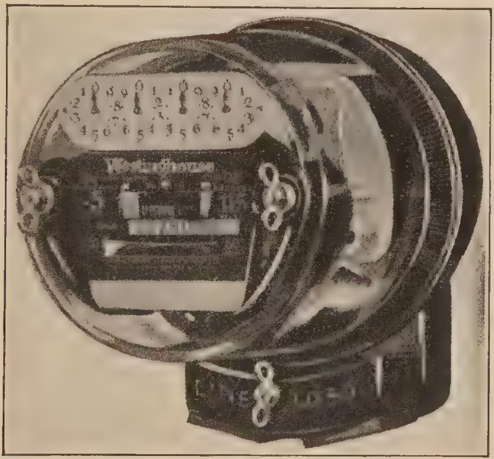


Fig. 12.—Westinghouse watt-hour meter. In 1924 the country's metered power and light bill amounted to approximately $1,335,000,000. One per cent greater accuracy in watt-hour meters would have made a difference of $13,000,000. One-half of 1 per cent would have amounted to $6,500,000.

age power factor for the month. The number 35,400 is the number of active kilowatt-hours and the number 70,800 is the total number of kilovolt-ampere-hours (kva.-hr.). A kilovolt is 1,000 volts.

Dividing the number of kilovolt-ampere-hours by the number of hours over which the measurement is taken gives the average number of kilovolt-amperes (kva.). Hence, the definition of the power factor, in its simplest sense, as in a single-phase system, is the ratio of the active kilowatts to the number of kilovolt-amperes. If the line voltage is constant, the wave form is sinusoidal, and the system is balanced, the simple definition reduces to the ratio of the number of active (working or running) amperes to the total number of amperes. Thus, it is seen that the total current consists of two components and is equal to the square root of the sum of their squares, when considered in the simplest aspect.

22. Quick Method of Finding the Power Factor.—Squaring quantities, adding their squares together, and then extracting the square root is a rather tedious process. G. B. Leland[1] has published Table IV which is used as follows: First, divide the number of reactive kilowatt-hours by the number of active kilowatt-hours. Referring to Fig. 9, for instance, the number of reactive kilowatt-hours is 61,320 and the number of active kilowatt-hours is 35,400. Their ratio is $\frac{61{,}320}{35{,}400} = 1.7321$. Referring to Table IV, the power factor corresponding to 1.7321 is 50 per cent. As another example, suppose the ratio of the reactive to the active kilowatt-hours was 0.9779. Then the power factor would be 71.5 per cent. Power factors are seldom shown on bills closer than the nearest tenth per cent. In Table IV, the power factor (lagging) is expressed in per cent and in that form is the cosine of the angle by which the total current lags behind the voltage, while the ratios which comprise the major portion of the table are the tangents of the angles represented by the corresponding cosines or power factors. When the power factor is unity, both the voltage and total current arrive at their respective maximum and zero values at the same instant, and all of the current is active or running current. This happens in incandescent lamps. When one becomes a maximum at the same instant that the other becomes equal to zero, the power

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[1] "Power-factor Table Lessens Billing Computations," *Elec. World*, vol. 81, p. 169, 1923.

TABLE IV.—TABLE FOR COMPUTING POWER FACTOR

Power factor	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
95	0.3288	0.3252	0.3214	0.3179	0.3143	0.3105	0.3067	0.3032	0.2994	0.2956
94	0.3630	0.3597	0.3564	0.3528	0.3495	0.3460	0.3427	0.3391	0.3356	0.3323
93	0.3953	0.3921	0.3889	0.3859	0.3825	0.3792	0.3762	0.3729	0.3696	0.3663
92	0.4258	0.4231	0.4200	0.4169	0.4139	0.4108	0.4078	0.4047	0.4015	0.3983
91	0.4557	0.4526	0.4498	0.4470	0.4438	0.4411	0.4379	0.4350	0.4320	0.4289
90	0.4843	0.4816	0.4788	0.4759	0.4731	0.4702	0.4672	0.4642	0.4614	0.4585
89	0.5123	0.5095	0.5068	0.5040	0.5011	0.4984	0.4957	0.4928	0.4899	0.4870
88	0.5398	0.5369	0.5343	0.5315	0.5287	0.5261	0.5233	0.5206	0.5178	0.5150
87	0.5667	0.5641	0.5614	0.5587	0.5560	0.5532	0.5505	0.5479	0.5452	0.5426
86	0.5934	0.5906	0.5881	0.5855	0.5828	0.5801	0.5774	0.5746	0.5721	0.5694
85	0.6196	0.6172	0.6144	0.6118	0.6092	0.6066	0.6040	0.6013	0.5987	0.5961
84	0.6459	0.6432	0.6408	0.6381	0.6354	0.6330	0.6301	0.6277	0.6249	0.6224
83	0.6720	0.6694	0.6669	0.6642	0.6615	0.6590	0.6565	0.6538	0.6511	0.6486
82	0.6980	0.6954	0.6929	0.6903	0.6877	0.6849	0.6824	0.6798	0.6773	0.6745
81	0.7239	0.7214	0.7188	0.7163	0.7135	0.7111	0.7085	0.7059	0.7032	0.7006
80	0.7499	0.7474	0.7447	0.7422	0.7395	0.7371	0.7344	0.7319	0.7292	0.7265
79	0.7761	0.7734	0.7708	0.7683	0.7657	0.7632	0.7604	0.7579	0.7552	0.7526
78	0.8023	0.7997	0.7971	0.7945	0.7919	0.7893	0.7865	0.7839	0.7813	0.7787
77	0.8287	0.8261	0.8234	0.8206	0.8180	0.8154	0.8127	0.8103	0.8077	0.8050
76	0.8551	0.8526	0.8498	0.8471	0.8446	0.8418	0.8391	0.8366	0.8339	0.8312
75	0.8819	0.8793	0.8765	0.8739	0.8711	0.8685	0.8657	0.8632	0.8603	0.8578
74	0.9089	0.9062	0.9036	0.9009	0.8980	0.8955	0.8928	0.8899	0.8873	0.8847
73	0.9363	0.9336	0.9306	0.9279	0.9252	0.9225	0.9198	0.9172	0.9145	0.9115
72	0.9637	0.9612	0.9584	0.9556	0.9528	0.9501	0.9473	0.9446	0.9418	0.9391
71	0.9919	0.9890	0.9861	0.9833	0.9807	0.9779	0.9750	0.9722	0.9694	0.9666
70	1.0203	1.0170	1.0144	1.0117	1.0088	1.0058	1.0032	1.0003	0.9974	0.9948
69	1.0489	1.0461	1.0431	1.0404	1.0373	1.0346	1.0316	1.0289	1.0259	1.0230
68	1.0783	1.0752	1.0724	1.0694	1.0664	1.0637	1.0606	1.0578	1.0547	1.0519
67	1.1080	1.1051	1.1020	1.0990	1.0961	1.0930	1.0900	1.0872	1.0840	1.0812
66	1.1383	1.1352	1.1323	1.1293	1.1260	1.1230	1.1200	1.1171	1.1139	1.1111
65	1.1692	1.1660	1.1629	1.1599	1.1568	1.1538	1.1506	1.1474	1.1443	1.1413
64	1.2005	1.1974	1.1943	1.1910	1.1878	1.1847	1.1816	1.1785	1.1754	1.1722
63	1.2327	1.2294	1.2261	1.2229	1.2198	1.2167	1.2135	1.2102	1.2070	1.2038
62	1.2655	1.2621	1.2589	1.2557	1.2523	1.2489	1.2458	1.2426	1.2393	1.2360
61	1.2989	1.2957	1.2923	1.2888	1.2857	1.2822	1.2788	1.2753	1.2723	1.2689
60	1.3335	1.3299	1.3262	1.3230	1.3194	1.3162	1.3127	1.3091	1.3059	1.3024
59	1.3684	1.3650	1.3613	1.3580	1.3543	1.3511	1.3473	1.3438	1.3404	1.3367
58	1.4045	1.4008	1.3972	1.3937	1.3899	1.3865	1.3827	1.3792	1.3755	1.3722
57	1.4415	1.4379	1.4340	1.4304	1.4266	1.4229	1.4193	1.4154	1.4120	1.4080
56	1.4792	1.4756	1.4718	1.4678	1.4641	1.4605	1.4565	1.4527	1.4490	1.4451
55	1.5185	1.5147	1.5105	1.5066	1.5027	1.4988	1.4951	1.4910	1.4872	1.4835
54	1.5587	1.5547	1.5507	1.5465	1.5425	1.5384	1.5345	1.5304	1.5262	1.5224
53	1.6000	1.5958	1.5916	1.5875	1.5834	1.5792	1.5751	1.5711	1.5667	1.5627
52	1.6426	1.6383	1.6340	1.6297	1.6255	1.6212	1.6170	1.6128	1.6083	1.6042
51	1.6864	1.6820	1.6775	1.6731	1.6687	1.6643	1.6599	1.6555	1.6512	1.6469
50	1.7321	1.7274	1.7228	1.7182	1.7136	1.7090	1.7045	1.6999	1.6954	1.6909

factor is equal to zero, and all of the current and energy is reactive.

23. Analysis of a Group of Power Bills.—Consider a case where a plant generates its own power with an engine-driven generator during the winter months when exhaust or bleeder steam is used for heating process and drying purposes, or for other processes, but the plant load is transferred to the utility's supply at noon and at night, and during the summer months. Table V shows the amounts of the bills for several months.

TABLE V.—POWER BILLS

Engine running		Engine not running	
Month	Amount	Month	Amount
March	$356.29	July	$740.23
April	454.94	August	828.19
May	372.01		
June	327.01		

A further analysis is given in Table VI.

TABLE VI.—SEPARATION OF THE CHARGES

Engine running

Month	Energy charge	Demand charge	Total bill	Power factor
March	$184.19	$172.10	$356.29	0.60
April	133.11	321.83	454.94	0.58
May	184.54	187.47	372.01	0.57
June	163.77	163.24	327.01	0.57

Engine not running

Month	Energy charge	Demand charge	Total bill	Power factor
July	$413.82	$326.41	$740.23	0.63
August	496.23	331.86	828.19	0.64

It will be noted that the demand charge for April is about the same as for July and August, while the demand charges for the other months when the engine was running average $174.27. When the demand charge jumps up like that, it looks suspicious and costs about $150 in this case. Perhaps someone threw over the plant load before it fell off naturally on that particular day, which usually can be learned by calling up the power company. However, such bills are often paid, and such items are discovered only when the bills are examined months afterward. It is a good plan to send the bills to the plant engineer, or someone else capable of making a simple analysis, to ascertain if any such additional expense has been incurred so that the cause may be remedied.

24. Finding the Plant Load Factor.—This requires a list of all of the motors and their name-plate data. While such lists are usually kept more or less up to date, often they may be made more complete. The card system is the best for this purpose and should include the manufacturer's guaranteed full-load kilowatt input for each motor, which may be obtained through the purchasing department. Then proceed as follows:

1. Find the average number of hours of operation per day for each motor and multiply it by the guaranteed full-load kilowatt input of each respective motor. This gives the number of kilowatt-hours per day for each motor on its guaranteed full-load-capacity basis.
2. Take the sum of the products in (1). This gives the total number of kilowatts-hours per day for all of the motors in operation on the full-rated-load basis.
3. Divide the total number of kilowatt-hours per day at the full-load (guaranteed) capacity, as found in (2), by the number of hours per day that the plant runs. This gives the average kilowatts that would result if all of the motors were fully loaded.
4. Find from the power bills or the active kilowatt-hour meter what the actual average number of kilowatt-hours per day is.
5. Divide (4), the actual average kilowatt-hours per day, by the number of hours per day that the plant is operated. This gives the average kilowatt input of the plant.
6. Divide (5), the average kilowatt input of the plant, by (3), the average kilowatts that would result if all of the motors were fully loaded. This gives the average load factor of the plant.

Example:

(1) MOTOR	RATED HORSEPOWER	GUARANTEED FULL-LOAD KILOWATT INPUT	HOURS PER DAY	KILOWATT-HOURS PER DAY
1	5	4.39	10	43.9
2	10	8.48	4	33.9
3	15	12.43	6	74.6
				152.4

(2) Total (guaranteed) number of kilowatt-hours per day for all of the motors in operation........................ 152.4

(3) Average kilowatts that would result if all of the motors were fully loaded throughout a 10-hr. day $\left(\frac{152.4}{10}\right)$..... 15.2

(4) Measured average plant kilowatt hours per day....... 46.0

(5) Average kilowatt input of the plant $(^{46}/_{10})$........... 4.6

(6) Average plant load factor $\left(\frac{4.6}{15.2}\right)$.................... 0.33

or 33 per cent.

This calculation allows for all motors that are shut down entirely, because the time they run is equal to zero and the products (1) of their guaranteed full-load kilowatt inputs and zero time are equal to zero. Hence, while they do not appear in the above tabulation, they are allowed for, just the same.

It is to be noted that the above method is based entirely on a survey and that no tests need be made. It also is to be observed that data could not be obtained on the motors not running during the period covered by the bills. Only a test of the motors would correct the average plant load factor to full plant capacity.

The load factors of individual motors are best found by test. It is important that at least one whole number of cycles of operation of the driven machine or machines be included in the test. To find the load factor of the motor under test, divide the average active kilowatt-hour indication by the product of the duration of the test in hours and the maximum demand in kilowatts. It is important that different loads be applied to the machines when convenient.

The weighted sum of the individual load factors must be equal to the plant load factor. To find the weighted sum, proceed as follows:

1. Multiply the average kilowatt-hours per day of each motor, as determined by test, by its average load factor.
2. Take the sum of the products obtained by (1).

3. Take the sum of the individual average kilowatt-hours of the motors.

4. Divide (2) by (3). The quotient is the weighted sum of the individual load factors.

As previously stated, the load factor of the plant shows what part of the plant has to carry the whole investment.

The above shows the necessity of knowing and increasing the value of the load factor which simultaneously increases the power factor where induction motors are used. Manufacturers of power-factor-corrective apparatus are educating power users as to the value of correcting their power factors for their own benefits regardless of any power-factor bonus or penalty that may be given by the utility. Plant engineers can gradually load their induction motors by proper substitution and by changing loads, and can use the salvage money on motors sold, or used for other drives where new motors otherwise would be needed, for improving the wiring, as by running new mains and branches or for purchasing connective apparatus.

Remotoring an old plant, where the loads can be even roughly estimated by noting their temperatures at the time of shut-down and by running them single phase, is not nearly so difficult as estimating the proper motors for new drives, as in new plants.

25. Some Suggestions.—When the purchase of an induction motor is contemplated, it may be advisable first to consider the use of a motor that will run with a power factor near unity and simultaneously supply magnetizing current to nearby induction motors. The proportion of the number of fractional-horsepower motors to those having greater horsepower outputs should be carefully watched, as the former motors have lower efficiencies and power factors than the latter. It is advisable to keep motors off the lighting circuit as much as practicable, especially when there is a greater charge for lighting energy than for the energy required for motors, since such motors are apt to cause variations and reductions in the illumination due to resistance drops. It is well to show the power bills to the man in charge of the electrical equipment and also to call his attention to the variations in the demand and energy charges, as well as the power factor, for the present bill and the bills for the last few months. Then suggest that he find why the demand is so great and also ascertain what motors are loafing. Then have the millwright look out for old bearings, poorly aligned shafting, overpull drives, too heavy and stiff belts, and too many individual drives. Then request the purchasing agent to stop buying belting except in special cases. The millwright will often find enough belting, especially in old plants, that can be reduced in width and thus save much friction and belt bending and if he goes after the belt situation in an energetic manner, he will soon have a stock that will last for a long time. All salvaged belting should be cleaned and treated with a good belt dressing. Then have the electrician and millwright get together, under the advice of the superintendent or plant engineer, and properly load the motors to increase the load factor and the power factor.

The men in the shop are apt to know where defective details are and should be encouraged through as much cooperation as possible in getting troubles corrected as soon as practicable after they are reported. The author has heard many confidential statements from such men who have shown him the conditions which were often very bad.

In isolated plants, or plants using auxiliary service, belt-driven generators are often not running at their rated speeds and, therefore, the motors are not being run at their rated speeds. Ask the engineer what the speed of the generator is, and then have him prove it right then and there. A Corliss engine may be turning over at, say, 90 r.p.m., which the engineer may state is the rated speed, and still the frequency may be off too much. These men often need some assistance from higher up, not alone through some article or book sent them, but through conversations and a real interest in their machinery and work. These men know the practical side all right, but little details like taking the generator speed now and then may not occur to them, as they are more apt to watch the r.p.m. of the engine.

CHAPTER V

TRANSMISSION, DISTRIBUTION, AND RATES

The consumer can learn much by studying a few of the utilities' problems and then comparing them with his own. One of these problems is the distribution system, which also is one of the problems of the consumer. The making of rates is an art and authorities differ as to how they should be made. Some of the reasons are herein discussed, the opinions of a number of authorities being given as to how the power factor should affect the rates.

26. Electric Transmission of Energy and the Railroads.—Both electric power companies and railroads transmit energy, the former over electric transmission lines and the latter by rail. The sources of the energy converted into electric energy and transmitted over transmission lines are chiefly falling water, coal and oil. The electric energy must flow continuously from its source to the consumers without even temporary storage, whereas the energy contained in the fuel transported by rail may temporarily be stored and the energy converted when desired, although the latter may be expensive.

In both cases, energy is required to transmit or to transport the energy delivered. In a general way, the time-rate of transmission or transportation of the energy stored in fuels is the power. Somewhat like the railroads, the electric utility companies are mostly subject to regulations by commissions who control the issuance of securities and fix the rates for service, since an electric public utility is a natural monopoly, that the confidence of the industries and the public may be maintained.

Some objects of long-distance transmission are successfully to compete with the railroads in the transmission of energy and furnish the power to operate the railways, as well as simultaneously to conserve and utilize the natural resources.

27. Extra Losses in Transmission Lines Due Exclusively to an 80 Per Cent Power Factor.—F. G. Baum[1] has shown that in a system having a load of 100,000 kw. at 80 per cent power factor, or equal to 125,000 kva., the total extra losses in transformers and transmission including main substations due to the 20 per cent difference between 80 and 100 per cent power factor amount to $14,000 per year for either water-power or steam-power conditions, the amount representing the value cost of water power at the power station or the cost of coal. The value of improved service has not been estimated in the foregoing. In addition, an extra burden is placed on the system due to the extra voltage required to overcome the drop in voltage over the reactance of the transformers, lines, and generators. The total burden may be 25 to 50 per cent of the installed lines, transformers, and generators.

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[1] "Atlas of U. S. A. Electric Power Industry," McGraw-Hill Book Company, Inc., New York, 1924.

The total rating of hydroelectric generators in the United States for 1925 was about 8,000,000 kva., representing only about 30 per cent of the total generator rating in central stations. The above figures do not include privately owned plants.

28. What H. P. Seelye[1] Says about Distribution Losses.—The following is taken *verbatim* from the first part of the article.

> There can be little doubt that the ideal of every company generating and distributing electrical energy is to generate and distribute that energy from coal pile to consumer's meter at the least possible cost, with due regard for service. This principle is so axiomatic as to need no discussion. It follows that every link in the chain connecting the consumer to the coal pile should be given careful attention to the end of developing its greatest economy both individually and also in relation to the other links. One very important link is the distribution system, fully as important as substation, transmission, or generation systems. It is a link, however, that is most apt to be neglected in the application of engineering principles of design.
>
> It would be inconceivable for a large generating station to be built or a high-tension transmission line to be constructed without consideration of the fact that economy of costs and carrying charges plays an important part in the design. But how much real thought is given on many systems to the economy of size and arrangement of primary feeders, distribution transformers, secondary mains, etc.? Yet all of the energy generated by that plant and transmitted by that transmission line must pass through this distribution system before it appears as salable energy at the customer's meter. The energy losses here will be fully as high as and perhaps much higher than in transmission lines and

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[1] Distribution Engineering Department, Detroit Edison Company. "Economics of the Distribution System," *Elec. World*, vol. 86, p. 107, 1925.

substations, and the investment represented is probably in most cases considerably greater. Often, however, the only thought given to it is to lay out a system that will operate and give the customer the service required, with perhaps in some cases a little consideration of Kelvin's law in determining the wire sizes. More often it is left to the line foreman on the job to put in what he sees fit.

Probably the reasons why the distribution system is sometimes overlooked lie in the facts that the distribution system is more widely scattered and hence less evident than other parts of the system and that the practical results obtained from engineering work on the distribution system are hard to show concretely. A large generating station is an imposing evidence of great investment to which one may point with pride. We can go and look at it and see the fires burning and hear the turbines roar. Power is handled in bulk and may be accurately measured; hence, any economies effected are readily discernible and may be clearly translated into dollars. Similar, in less degree, are the transmission lines and substations. But for the distribution system we are more likely to visualize a more or less unsightly line of wood poles and a maze of wires which occupy our back alleys and which are a necessary evil, but which we would like to forget lest we feel apologetic. Yet

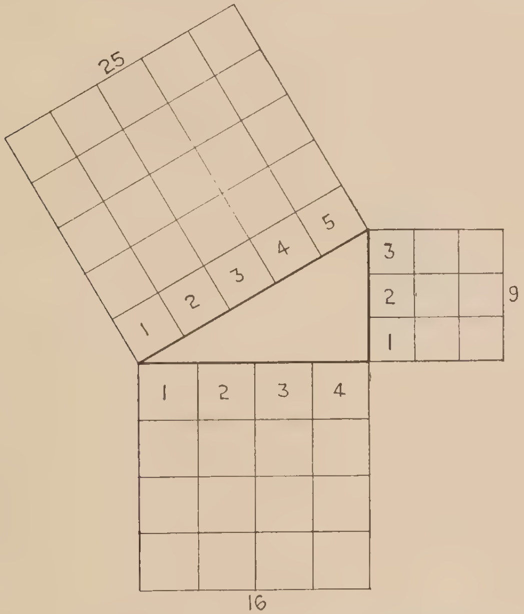

Fig. 13.—Principle of geometric addition and subtraction.

that distribution system probably represents nearly as large a part of our total property as the generating station. Also it is very difficult to show tangible results of economies applied to this system. It is so widespread, the loads carried are so diversified and so variable, both in demand and in consumption, from day to day and year to year, and are metered at so many different points that any very definite exhibit of actual results accomplished is often well nigh impossible. This should be evident, it is true, in the final analysis of yearly investment and operating costs for the system, but even here there are so many other contributing facts that it is difficult to state confidently that any particular effects are the results of economies on the distribution system. For it may be found that real economy lies in increasing the investment to lower the losses, or conversely, that an increase in losses may effect a greater economy in investment. We must ask rather that the economies we can exhibit be accepted as representative of others fully as large which we can only compute; that the percentage economy we can figure for the small individual job be considered to apply similarly to the large general class of similar jobs. It is the purpose of this article to show something of the importance of the distribution system and the magnitude of some of the results that may be expected from the applications of engineering principles to its design.

It might be well, first, to define our use of the term distribution system. In one sense, the whole system, outside of the generating station, is the distribution system in that it distributes the energy generated. In a more limited sense, however, we may generally subdivide this into a transmission system, substations, and the local distribution system which distributes to the customers from the points of concentration, the substations. Although the problem of economical distribution includes all parts of the system and they will all be included to some extent in this discussion, it is desired to emphasize especially the local distribution system as that part which is often least considered.

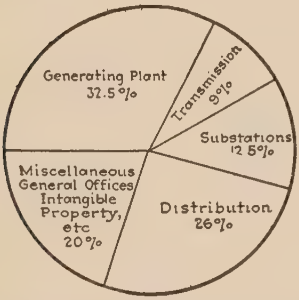

Fig. 14.—Division of total investment in a central-station system.

The importance of this distribution system as a part of the power company's property is best exemplified by the proportion of the total property investment which it represents. This will, of course, vary somewhat with the nature of the company and the type of loads served. The accompanying diagram gives an example of one company carrying a general diversified load of power, light, street railway, etc. It is probable that the figures of other companies of a similar character will not be widely different. It will be seen that the investment necessary for the distribution of the energy generated (including transmission and substations) is nearly 50 per cent of the total investment of the company and 50 per cent greater than that in the generating plants. Of this more than half is in the local distribution system—that is, primaries, transformers, secondaries, etc.—and this alone is nearly as great as the investment in the generating plants. As a concrete example, if the system had a total property value of $25,000,000, on the basis of the division shown in the diagram the generating plants would represent about $8,100,000, the whole system of distribution about $12,000,000. Of this, transmission would represent $2,300,000, substations $3,200,000, and local distribution $6,500,000.

LOSSES IN DISTRIBUTION

The proportion of the energy generated that is lost in its distribution depends somewhat, of course, on the type of loads carried as well as on the design of the system. If a large amount of power is wholesaled at primary transmission voltages, the general percentage for the whole system will be lower on account of the fact that the customer in this case pays for transformer and secondary losses. Considering power that is sold at secondary voltage, however, the loss is probably somewhere between 10 and 30 per cent, according to the system; that is, for a system generating 300,000,000 kw.-hr. during the year, from 45,000,000 to 90,000,0000 kw.-hr. will be lost in distributing it to the customers. If the cost averages 1 ct. per kilowatt-hour, including all charges up to the point of utilization, which for most systems with steam generation is probably low, this loss would amount to $450,000 to $900,000 per year, a not insignificant figure. Of this, the local distribution system may take one-half or more, the remainder being used in substation and transmission.

I should like to state at this point that these figures are presented not as generally representative of any system or type of system, as the division of the investment and per cent of losses would not be alike on any two systems. They are given simply to illustrate the magnitude of the investment and losses pertaining to the distribution system. They were based, however, on actual values for a known case, and it is probable that the proportions for other systems would be of a similar magnitude.

In this connection also the figures published recently in the *Electrical World* (Mar. 14, 1925) on the value of additions to generating, transmission, and distribution systems in the United States for several years are interesting. These show that over a period of five years from 1921 to 1925 the total cost of these additions and extensions is divided as follows:

	Per Cent		Per Cent
Generating plants	49.3		
Transmission (including substations)	21.2	Transmission and distribution	50.7
Distribution	29.5		

The same authority gives figures for the total central-station energy generated and sold during the months of October, November, and December, 1924. The difference amounts to 19.3 per cent of the total generated. Part of this is energy used by the companies themselves, but this would be probably not more than 1 per cent in most cases. Since a part of this is wholesaled, it is apparent that the figures given above for losses on secondary retail power are more or less substantiated.

The object in presenting these figures is not simply to show what is well known, that we spend a great deal of money and lose a large part of the energy in distributing it. Rather it is to bring out the fact that the system of distribution as a whole and the local distribution system in particular are relatively large factors in the total cost of producing and selling energy and as such warrant as much attention and engineering skill as are granted to other parts of the property. W. S. Murray in a recent letter to the *Electrical World* says that "80 per cent of the cost of power to the consumer lies in getting that power to the consumer after it has been generated." We cannot distribute energy without losses and we must expect a large investment in the distribution system, but it behooves us to see that the money is wisely spent and that those losses are not greater than is consistent with economy. In fact, the widespread nature of the distribution system and the difficulty of accurately checking results would indicate the greater necessity for correct engineering and the continuous application of economic study to its installations and its subsequent operation.

29. Rates.—The general principle of making rates for electric service is that the utility should receive sufficient revenue to pay operating expenses, interest, taxes, insurance, depreciation, and a fair profit on the enterprise.

The two general theories are the value-of-service theory and the cost-of-service theory, the latter assuming that all rates should be proportioned among the various classes of customers according to the cost of serving them.

There are two general forms of rate, namely, the meter rate, which is applicable only to the number of kilowatt-hours of electric energy consumed by a customer, and the demand rate, which applies to any method of charge for electric service based upon the number of kilowatts of electric power demanded by the customer during a given time interval, although the demand may be based upon, or may be a function of, the use, or size, of the customer's installation. Power-factor rates generally are included in the demand rate.

The term "straight meter rate" indicates that the price charged per kilowatt-hour is constant regardless of the number of kilowatt-hours consumed. In the step meter rate a certain specified price per kilowatt-hour is charged for the entire energy consumption per month or other customary period, the rate depending upon the particular step within which the total energy consumption falls. In the block meter rate a certain specified price per kilowatt-hour is charged for all or any part of a block of such a unit.

The term "flat demand rate" refers to a charge for electric service based upon the customer's installation or energy-consuming apparatus, and is usually so much per watt or per kilowatt per month or per year. Sometimes this type of rate is nominally so much per customer per year, or per month, for each of the various classes of customers, but estimated demand and quantity of energy to be used have important bearings on the determination of the class. The rate may be modified by the block or step methods.

The Hopkinson demand rate, proposed by Dr. John Hopkinson[1] in 1892, also known as the two-charge rate, applies to that method of charge which consists of a demand charge, a sum based upon the demand, either estimated or measured, or the connected load, plus an energy charge based upon the quantity of energy consumed. Either the demand charge or the energy charge, or both, may be of the block form, as in Tables II and III.

The Wright demand rate, proposed by Arthur Wright[2] in 1896, is that wherein a maximum price is made for a certain amount of energy, and one or more reduced prices per unit, as per kilowatt, are charged for the balance, on the block principle, in accordance with a schedule based upon the use of the maximum demand.

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[1] "On the Cost of Electric Supply," in which he proved that the total cost of electric supply could not be correctly stated as so much per unit unless the rate of supplying that unit also be stated, and that with what is now called low load factor the unit cost depends much more upon capital and standing charges than upon the running costs, which continue from hour to hour.

[2] Engineer-manager of the Brighton plant, who, in a classical paper, showed from records of that plant that the additional number of kilowatt-hours delivered to customers during the winter months was produced at a very slightly increased total cost above the costs incurred to deliver the much smaller number of kilowatt-hours delivered during the summer evenings. He also is the inventor of the Wright demand indicator.

The Doherty or three-charge rate, proposed by Henry Doherty in 1900, which may be expressed in either the block or step form, applies to that method of charging which consists of the sum of (1) a charge per customer or per meter; (2) a demand charge based upon the demand, either estimated or measured, or the connected load; and (3) an energy charge based upon the quantity of energy consumed.

30. Demand Rates.—The meter rate, which is applicable only to the amount of electric energy consumed by a customer, is simplicity itself. The demand rate, however, is not quite so simple in practice. W. M. Carpenter[1] found during an investigation[2] that there was a great diversity in the methods employed by the various utilities in connection with their demand rates.

> There are on file in Albany and New York over one hundred rates, of which hardly five are alike. The time interval varies from an "instantaneous" reading to one hour. Some companies carry the demand, once established, over a period of an entire year; others carry it for a month; a few special cases are for a week only. Some companies, in a happy uncertainty, do not define "demand" at all; others compute it, not from the readings of recording or indicating instruments, but as a percentage of the connected load, and here also there is a wide range of practice.
>
> Much of the business affected by demand rates is obtained in competition with private plants. The manufacturer always has steam boilers in his factory, and it is not such an enormous step to increase his equipment a little and install an electric plant in addition. If the manufacturer thinks that he can make electricity more cheaply himself, he certainly will do so. The scores of isolated manufacturing power plants[3] within the limits of the larger cities of the state bear abundant witness to this fact. The large consumer, usually having at least a boiler house,

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[1] Chief Engineer, Electric Meter Section, Empire State Gas and Electric Association.

[2] In a paper presented before that section at Syracuse, N. Y., Jan. 22, 1924, and published in *Elec. World*, vol. 81, p. 1,459, 1924.

[3] 37.5 per cent of the 31 billion kilowatt-hours consumed in 1924 by all industries of the United States was generated in private plants, the remaining 62.5 per cent being purchased from central-station companies. Hence, the private plants generated 60 per cent as much energy as was purchased from the central-station companies.—Editor.

sometimes even generating machinery of his own, is often in a position of considerable independence and can bring this additional factor to bear upon the question. For this reason the purely engineering considerations are often modified so as to obtain a piece of business for which special provisions must be made.

A typical afternoon's work of an iron foundry, in the load of which are included a 250-hp. air compressor, an electrically driven crane, and the usual tumbling barrels, and miscellaneous machinery, is shown by the graphic wattmeter chart in Fig. 15. If, when the evening lighting load is on, all these happen to operate simultaneously, a considerable peak is formed.

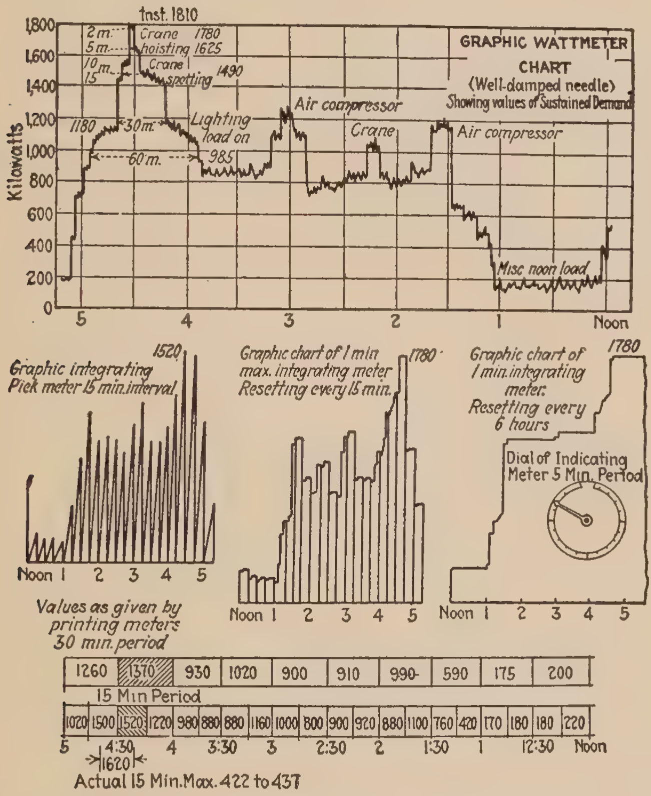
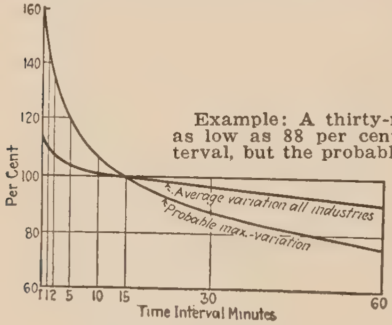


FIG. 15.—Curve showing variation of results by using different time intervals for measuring demand as compared with 15-min. interval.

The fundamental difficulty of the whole subject appears to center in the time interval, and while many arguments have been submitted in favor of each particular unit of measurement, the great majority of rates are based on questions of policy rather than upon scientific or engineering facts. The entire question is influenced by broad considerations of rate making, but it is desirable to note what a great difference in the size of the customer's bill will be caused by various methods of measurement.

From the chart in Fig. 15,

. . . it is easy to determine how the various time intervals will affect the amount of the so-called demand. If the "sustained" peak is used as the basis of measurement, the demand found will be lower than where the "integrated" peak is used, and the unit price will have to raised accordingly. The sustained peak may be defined as that portion of the curve during which the indication remains at its highest value for the duration of the required period of time. While the use of this quantity —in that it cannot exceed the true maximum integrated demand— will usually meet the customer's entire approval, it is very unfair to the electric company because the value cannot be higher than the minimum point of any depression which may occur during the period. In addition, the depth of the instantaneous minimum as drawn by graphic instruments depends largely upon the amount by which the meter movement is damped. It is also possible for unscrupulous customers to install artificial interrupting devices which will cut off the current long enough to let the needle drop and then pick it up again. From the chart it is evident that a 60-min. sustained demand will only show 985 kw., while a 15-min. period will give 1,400 kw. and a 2-min. one will give 1,780 kw. Similar, though not so extreme, differences are shown by various methods of integration, which give either the actual or else the average kilowatts used in any period of time. To the left below the



Example: A thirty-minute interval may show as low as 88 per cent of the fifteen-minute interval, but the probable average of all industries will be 97 per cent of the fifteen-minute reading. An instantaneous interval may be as much as 160 per cent of the fifteen-minute period, but the probable average of all industries will be 116 per cent of the fifteen-minute values.

Fig. 16.—Curve showing variation of results by using different time intervals for measuring demand as compared with 15-min. interval.

wattmeter chart is shown how the curve might look on a graphic integrating meter of the "Piek" type, which resets on a 15-min. period. This would show 1,520 kw. A 1-min. maximum integrating meter would show 1,780 kw., while a 5-min. period would give 1,670 kw.

Figure 16 appears to show that the 15-min. peak comes as near as may be expected to the probable average of all industries.

The foregoing is based on an exhaustive study by Mr. Carpenter of a tabulation of all demand rates then in effect throughout the state, and also through questionnaires to the larger companies.

Table VII,[1] compiled by Mr. Carpenter, is based on the data taken at random from graphic wattmeter charts of typical industries, and represent an ordinary day's work. From these, peaks were selected and the relation of values found by using the various time intervals shown. This table indicates the importance of a careful consideration of the time interval and kind of metering device which should be adopted for measuring the demand. The table appears to bear out the experience of most companies that a 15-min. peak is the most satisfactory and representative of the average maximum demand.

31. A "Yardstick" for Grading Public Utilities.—While the utilities are restricted monopolies, the utility business must be conducted for profit. Whatever is left after the expenses are paid goes toward reserves for depreciation, taxes, return on investment, and profit.

G. H. Pike[2] describes a method used by many utility men but not used or understood by a great many others. There are wide gaps between the various measuring units thus far devised, and the "yardstick" described has often brought out the real point in a general problem.

The factors involved are:

1. The commercial value of the business.
2. The operating ratio[3] in per cent.
3. The fixed charges in per cent.
4. The gross revenue per year.

The commercial value of the business is then found by first taking the ratio of (4), the gross revenue per year, to (3), the

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[1] "Effect of Time Interval and Type of Load upon Integrated Kilowatt-hour Demand," *Elec. World*, vol. 82, p. 443, 1923.

[2] *Elec. World*, vol. 81, p. 750, 1923.

[3] Ratio of expenses to revenues.

TABLE VII.—INTEGRATED DEMAND AS MEASURED BY VARIOUS LENGTHS OF PEAKS COMPARED WITH ACTUAL USE IN MAXIMUM HOUR

Industry	1 hr., kilowatts	Per cent of hourly demand	30 min., kilowatts	Per cent of hourly demand	15 min., kilowatts	Per cent of hourly demand	10 min., kilowatts	Per cent of hourly demand	5 min., kilowatts	Per cent of hourly demand	2 min., kilowatts	Per cent of hourly demand	Instantaneous, kilowatts	Per cent of hourly demand
Steady loads:														
Pumping plant	154	100	154	100	154	100	154	100	154	100	154	100	154	100
Flour mill	5,000	100	5,000	100	5,000	100	5,000	100	5,000	100	5,000	100	5,250	105
Flour mill	510	100	525	103	530	104	530	104	540	106	540	106	560	110
Refrigeration	930	100	940	101	965	104	980	105	1,000	107	1,005	108	1,020	110
Refrigeration (bottling works)	600	100	625	102	630	103	635	104	640	105	640	105	740	121
Refrigeration (ice-cream manufacturing)	128	100	130	101	132	103	132	103	132	103	134	105	137	107
Refrigeration (cold storage)	84	100	85	101	88	105	90	107	91	108	91	108	98	117
Refrigeration (cold storage)	130	100	135	104	138	106	140	108	145	111	146	112	148	114
Electric furnace	430	100	440	102	440	102	445	103	450	105	460	107	460	107
Electric furnace	370	100	378	102	380	103	380	103	380	103	380	103	385	104
Electric furnace	200	100	215	107	220	110	225	113	225	113	230	115	240	120
Electric furnace	110	100	110	100	110	100	110	100	115	104	120	109	150	136
Paper mill	4,250	100	4,500	106	4,550	107	4,600	108	4,700	111	4,800	113	5,150	121
Paper mill	750	100	760	101	785	104	790	105	790	105	790	105	840	112
Paper mill	520	100	590	113	640	123	660	127	670	129	670	129	680	131
Paper mill	455	100	480	105	500	110	500	110	500	110	500	110	520	114
Paper mill	360	100	380	105	390	108	382	109	400	111	400	111	410	114
Wallpaper manufacturing	410	100	440	107	440	107	445	108	450	109	450	109	460	112
Talc mill	1,070	100	1,170	109	1,170	109	1,170	109	1,170	109	1,170	109	1,170	109
Fertilizer mill	112	100	116	103	125	111	135	120	135	122	138	127	140	125
Average of group	......	100	......	103.6	......	106	......	107.3	......	108.6	......	109.3	......	114.3

Intermittent loads:														
Machine shop	1,150	100	1,160	101	1,180	102	1,200	104	1,210	105	1,220	106	1,300	113
Machine shop	355	100	355	100	360	101	370	104	372	105	375	106	425	120
Machine shop	168	100	200	119	210	125	215	128	220	131	220	131	272	162
Machine (railway shop)	108	100	113	104	118	109	120	111	126	116	130	120	140	130
Machine (railway shop)	74	100	90	107	97	115	98	117	100	119	100	119	112	151
Packing house	49	100	64	131	66	135	67	137	75	153	80	163	82	166
Office building (hydraulic elevators)	90	100	90	100	90	100	90	100	120	133	125	139	138	154
Lithographing shop	290	100	325	112	340	117	345	122	360	124	360	124	381	131
Evening newspaper	540	100	620	115	690	128	710	131	740	137	750	139	800	148
City street railroad	5,500	100	6,220	113	6,450	117	6,500	118	6,500	118	6,500	118	6,900	125
Foundry	140	100	145	103	148	105	149	106	149	106	150	107	165	118
Stone crusher	360	100	370	103	380	105	400	111	415	115	420	117	465	129
Lumber mill	550	100	560	102	600	109	615	112	620	113	640	116	760	138
Average of group	......	100	......	108.3	......	112.8	......	115.5	......	121	......	123.4	......	137.2
Heavy metal-working loads:														
Foundry with electric cranes	1,300	100	1,525	117	1,620	124	1,625	125	1,720	132	1,780	137	1,810	139
Brass rolling mill	3,600	100	4,100	105	4,200	108	4,250	109	4,300	110	4,350	111	4,600	128
Iron rolling mill	4,200	100	4,800	109	5,050	115	5,060	115	5,400	123	5,800	132	7,200	171
Iron rolling mill	1,600	100	1,600	100	1,700	106	1,800	112	1,900	119	1,900	119	2,500	156
Average of group	......	100	......	107.7	......	113.2	......	115.2	......	121	......	124.7	......	148.5

fixed charges in per cent, and then multiplying the ratio thus found by (100 – item (2)).

As an example, let it be assumed that after a utility's taxes are paid, its operating ratio is 64 per cent, and its total fixed charges are 12 per cent (depreciation 4 per cent and interest 8 per cent), and gross revenue $100,000 per year. Then the commercial value of the business is calculated as follows: $\frac{\$100,000}{12} =$ $8,333.33. 100 -- 64 = 36. $8,333.33 × 36 = $300,000, or the commercial value of the business is equal to $\$100,000 \times \frac{(100-64)}{12}$ = $100,000 × 3 = $300,000. Upon looking over the utility's books, however, it may be found that the plant assets amount to $500,000.

Now we may go to work to answer the question involved. Let us make some more assumptions. Possibly the utility's expenses should be reduced; maybe it needs a rate increase to increase revenues. Either one of the measures will improve the operating ratio. Maybe service is poor and revenues are low for that reason. Maybe there has been too much high-priced construction, perhaps some foolish construction. Possibly the business is still undeveloped and it may be necessary to make rate changes before development can be attempted. I might add here that rate changes do not always mean rate reductions. Some of my readers might be surprised if they, for instance, converted oil-engine costs into an equivalent demand and energy charge, and I believe too much attention has been given heretofore to cutting costs, and insufficient attention paid to what our competitors really can do.

Possibly fixed charges were estimated too high. Suppose we choose 4 per cent depreciation and 6 per cent interest, or 10 per cent total. Then: $\$100,000 \times \frac{(100-64)}{10} = \$360,000.$

I do this to show that it is very important to make the proper assumptions as to the so-called fixed conditions which hold with any particular property. Investigation might disclose that business could be increased 10 per cent and operating expenses cut 10 per cent and that 10 per cent was the right fixed charge. Then:

$$\$100,000 \times \frac{(100-53)}{10} = \$470,000.$$

This now almost balances our assumed book value and shows a nearly healthy financial and operating condition. There is a temptation here to juggle the values in this equation until it fits the case. This, however, destroys its value as a guide.

I have discussed this subject merely to bring home again to some, and possibly for the first time to others, the importance of this "blanket yardstick," which really covers the whole field of operations of any particular utility, or, in fact, any business which keeps a proper accounting record.

32. Rate Making an Art.—Alex Dow[1] has reviewed[2] the general subject and has given credit to the classical papers of Dr. John Hopkinson (1892), Arthur Wright (1896), and W. J. Greene (1896) for much that has clarified the process of rate making. Some excerpts follow:

> A reading of these three papers will show that by 1896 the analysis of the cost of service was already almost complete. There was recognition of diversity factor and of load factor, for which latter useful expression the industry is indebted to Colonel Crompton. We had begun to speak of customer costs and of demand costs and of costs proportional to the energy metered. The defect of a rate method which encouraged the short-hour consumer had been clearly recognized. The sale of central electric power for continuous use in industries was still a small source of revenue compared with lighting, and the makers of rate schedules looked upon the power business as the sale of a by-product. Service was still sold at flat rates—so much per connected lamp per month—or was sold by meter at so much per lamp-hour; but practical and accurate energy meters giving correct readings on dials were on the market, and the use of the kilowatt-hour as the measure of electric service was a matter of law in some localities and a rapidly spreading custom in all localities.
>
> During that decade the fashion of selling service by the kilowatt-hour became almost universal. A special rate was made, of course, for power service, which entailed the use of separate meters for power and lighting on the same premises. The rate theory taking account of load factor was reduced to practice only by a few of the more progressive managements. While experience, costly in many cases, has taught that each and every kilowatt-hour could not be sold safely or competitively at the same rate, the adjustment of rates to cost, if made at all, was made by the establishment of numerous class rates, and by trial and error—instead of analysis.
>
> We are far from the general acceptance of any complete theory of rates, but within the industry we are fairly agreed upon important principles. There is still much empirical rate making. I believe that

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[1] President of Detroit Edison Company.

[2] "Evolution of Rate Making," *Elec. World*, vol. 84, p. 629, 1924.

empiricism persists because, after all, the ultimate test of a rate schedule is whether it serves to settle accounts to the satisfaction of both parties. There are lots of rate schedules in which adaptation has to be sacrificed to superficial simplicity. Conversely, there are rate schedules which are injuriously complex.

I have wished more than once in the course of my years of service on the rate-research committee of the National Electric Light Association that my committee had some such power as was attributed to it by malicious critics, to dictate the making of rates and rate schedules. I would willingly have used that power to prevent the making of cruel and unusual forms of electric rates and to abolish some that I found in existence and I would with equal willingness have dealt harshly with the manager who was hurting his business by an arbitrary schedule which had no merit except brevity, and wrongfully laying a large share of service costs upon customers who had done little to incur those costs.

Thus far I have talked in terms of cost of service. But our studies of the last twenty years have recognized the element of value of service and the necessary apportionment of the burden of a reasonable profit to different classes of service according to the willingness and ability of each class to earn its share thereof. The immense increase in the use of our energy by industries which heretofore have produced their own electric power and could continue to do so has taught us the value of service to these industrial consumers. They would not use it unless it paid them to use it. We have also learned the value of that industrial business to our non-industrial customers, who have profited by the reduction of our costs through the increased output which the industrial sales have made possible. The extension of domestic electric service to the smallest households has put us in touch with the ultimate consumer, and in dealing with him we have learned and practiced the economic rule that service to the small consumer will become cheap to him and profitable to the company if every such consumer is served at the rate which encourages him to use our service liberally.

Finally, we have learned that theory is a necessary guide in rate making, but that because rates must be made for the future, the analysis of past costs cannot be any more than a guide and that rate making is an art.

33. Kilovolt-ampere Basis of Demand.—If the demand could be expressed in kilovolt-amperes and the energy in kilowatts (as at present), the power factor would not appear at all and it would be a much easier matter simply to bill the customer for the demand under the new term and for the energy at, perhaps, a different rate. This basis for billing demand has been proposed and discussed many times.

The following excerpts are from an article[1] by J. E. Doran, J. B. Hodtum, and R. C. Fryer.

> For a group of representative companies, inventories show chargeable to used and unused physical property for electrical production and distribution an average of $9,974,201. Of this, $1,585,152 is chargeable to steam equipment only, or 15.8 per cent of the total amount chargeable to electrical production and distribution. A kilowatt demand could be considered as proportional, within certain limits, to only 15.8 per cent of the total investment charge. The remaining 84.2 per cent represents the cost of generators, substation and transformer equipment, underground and overhead lines, etc., for which the central-station company is paying the manufacturer upon a kilovolt-ampere basis. The central station is selling this capacity to its customers on a kilowatt basis. To establish the lack of equity in basing the demand charges upon a kilowatt basis, it is necessary to remember only that any customer with a low power factor is using, without charge, more units of system capacity throughout the major portion of the investment serving him than he is paying for. If, for every kilovolt-ampere supplied, a customer is using a direct proportion of 84 per cent of the investment, it seems sound economics to collect demand charges upon that basis.
>
> A kilowatt does not represent the total demand even against that portion of the investment chargeable to steam because the coal pile is carrying the energy losses due to effective idle or magnetizing current at low power factor. This loss is variable, dependent upon the effective idle amperes and the resistance in the system circuits. Therefore, at any power factor other than unity the kilowatt does not represent a true proportion for measurement of demand against the steam investment, which in the specific example is shown to be 15.8 per cent.

Arthur Wright, noted English inventor and consulting engineer, on a visit to the United States, made the following statements:[2]

> A perusal of some of the recent schedules of rates, especially those dealing with power factor, will convince many that the time has arrived for us to come back to earth again and to realize where this so-called scientific rate making is leading us. If in the early days of alternating-current motors the rate for this class of customers had been studied, it could have been very easily and finally solved by insisting on the demand being measured in kilovolt-amperes and the energy in kilowatts.

[1] "Kilovolt-ampere Basis Favored for Demand Billing," *Elec. World*, vol. 79, 1922.

[2] As reported in *Elec. World.*, vol. 85, p. 141, 1925.

> Thus the question of power factor need never have arisen; in fact, the whole trouble has been self-inflicted by our having approached the problem from an entirely artificial point of view. When it is realized that practically the whole of the generating and distribution investment is bought on a kilovolt-ampere basis (the steam-producing equipment being the exception) and that nearly 80 per cent of the total charges against revenue in an average utility company are independent of the actual kilowatt-hours turned out from it, it is interesting to inquire how the mistake of selling service on a kilowatt-hour basis arose.
>
> Owing to the great superiority of the Thomson-Houston watt-hour meter over the older ampere-hour meters (such as the Schallenberg and others), the watt-hour basis took the field in theory and practice for the only market then existing—electric lighting. The wonderful simplicity and accuracy of the Thomson-Houston meter with its intrinsic allowance for voltage fluctuations inculcated the idea in the United States that watt-hours should be measured and not that ampere-hours should be measured and then multiplied by the supply voltage. In Europe this necessity of volt measurement was never very pronounced, and the ampere-hour meters are still very extensively used for direct-current supply systems. Again, in these early days it was thought that the charges for the service should and could be made nearly proportionate to the supposed cost of generation and distribution of the energy, and as the whole business was then electric lighting, the energy consumed was proportional to the current multiplied by the supply voltage, and thus the kilowatt-hour basis was firmly established before the alternating-current induction motor appeared on the scene.

There is much more to the article quoted.

A. S. Knight,[1] in an article[2] commenting upon the statements by Arthur Wright, defends the present rate forms and discusses the problems of the large consumer and the small consumer.

> In the case of the large consumers there is no excuse for a company which also allows such customers to operate with abnormally low power factors, as there is no doubt that it is entirely practicable to oblige such customers to bring their power factors up to a reasonable standard. The problem in the case of the small consumers, however, is more difficult, although it is not the desire to "invent more scientific self-fooling tariffs" which have prevented the introduction of power-factor penalties to these small consumers. The whole question is whether it is better to average the power-factor losses of small consumers over the business of the high and low power-factor consumers or

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[1] Public Utility Consultant, Boston, Mass.

[2] "Economic Aspects of Power-factor Correction," *Elec. World*, vol. 85, p. 662, 1925.

to attempt to collect these losses from the customers using them. It must be remembered that the companies are now collecting these losses, if their total incomes are correct, so that it is principally a question whether the present distribution of the companies' costs between customers is unfair to the higher power-factor consumers. In this connection it should be remembered that most of the companies have regulations which attempt to keep individual power factors within reasonable limits by prohibiting service to extremely low power-factor consumers.

CHAPTER VI

SYMPOSIUM ON THE POWER-FACTOR SITUATION

The opinions and experiences of some authorities on the general subject, as viewed from various angles, with statements as to how power-factor correction has been successfully applied and the benefits derived therefrom, together with the present situation and some interesting historical information, are given in this chapter. The early use of static condensers for the improvement of the individual power factors of two-phase and three-phase motors, connected directly across the motor terminals, by William Stanley, an electrical genius of 35 years ago, is noteworthy.

34. Charles J. Russell.[1]

The gradual introduction of power-factor clauses in central-station schedules of rates has indicated some recognition of the importance of the subject. At present, however, it may be said that a general condition of apathy exists in regard to this matter throughout the industry and that very little constructive work is being done toward the solution of existing problems in power-factor control.

Power-factor clauses now exist in the rate schedules of a hundred central stations. Investigation of the form and operation of these clauses shows a great lack of uniformity in the bases upon which they are formulated. In the majority of cases where penalties are provided for low power factor they are not enforced and the clauses are considered as a police measure to be enforced at will.

In the meantime motor loads are increasing by leaps and bounds, and it must be anticipated that the power-factor situation will daily become more general and more serious. In many cases new business is being put on without reference to power factor, and the rapid expansion of the small-motor business is continually increasing the amount of reactive capacity to be supplied by the central station without compensation.

The negative points that seem responsible for the lack of action in power-factor work are somewhat as follows:

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[1] Vice-president Philadelphia Electric Company. "The Present Power-factor Situation," *Elec. World*, vol. 84, p. 674, 1924.

1. Doubt in the minds of central-station executives as to the proper way to approach the solution of the problem.
2. Fear of the results of action along the lines of penalties or bonus additions to schedules of power rates.
3. A lack of agreement as to the proper methods of measurement of power factor.
4. General failure to appreciate the importance of good power factors to the customer as well as to the central station.

All these negative points have little foundation as real reasons for not reaching an agreement in handling power factor. The engineering phases of the power-factor question are well understood, although the cost due to low power factor and the cost of correction of low power factor must be calculated for a system, a part of a system, or for any individual installation.

Within a year or so, there has appeared upon the market a motor which operates at unity power factor and which may supply sufficient leading current to correct to a certain degree a low power factor existing in the same installation. Announcements have also been made relative to high-power-factor motors which are being put out by other companies. These motors should be investigated and receive the interest and support of the whole central-station industry.

Within the last two years, there has been a large amount of power-factor-corrective work done in the distribution systems of some large companies. The investment, cost of operation, and maintenance of the corrective apparatus are, of course, placed upon all customers of the company, although the necessity for these items of cost has been brought about by the bad effects of a single class of central-station customers.[1]

The present situation is regrettable in that serious consideration has not been given to the mutual advantages to customer and company of maintaining a high power factor. Sooner or later interest in the subject must be revived, but in the meantime the problems which must be solved in the future are growing larger and larger.

35. W. A. Layman.[2]

There are a number of astonishing features connected with the power-factor problem. It has existed for 30 years, and yet it is necessary to define it in simple terms understandable to the general public. It involves serious questions of finance and executive management, and yet it is isolated in the engineering ward of our electrical hospital. Other great problems of the alternating-current system of distribution have been energetically attacked and solved, and yet this has persisted

[1] Using, say, 100 kw. and less.—Editor.

[2] President of Wagner Electric Corporation. "Thirty Years of the Power-factor Problem," *Elec. World*, vol. 84, p. 791, 1924.

for 30 years, relatively untouched by the march of electrical progress. It is the caudal appendage of the industry, inevitable in our early stages of evolution, but now unnecessary, yet persistently trailing us, unsightly, bothersome, destructive, costly.

With some of us this problem has been an ever-present, inescapable nightmare. I came into the industry at the time the large alternating-current plants were beginning to give 24-hour service—then limited practically to incandescent lighting. At once, "magnetizing current" (we called it "leakage" current then) of distribution transformers became a serious operating consideration. To me was assigned the task of designing and testing transformers with smaller "leakage current." The inadequacy, by the way, of the terms we have applied to this phenomenon ("leakage" current, "idle" current and so on), their inaccuracy from the strict engineering point of view, has been one of the symptoms and also one of the causes of the persistence of the problem.

Our principal customer, the old Missouri Light and Power Company of St. Louis, imperatively demanded better transformers from the standpoint of "leakage" current. Most of this company's generating units were of 125-kw. capacity each, and two or three of these units were operated at times with full-load current during daylight hours, although the actual energy load was insignificant. The leading manufacturing companies responded aggressively with better transformers, and the transformer art progressed rapidly to a fairly comparable stage with the excellent apparatus of today.

PROBLEMS BROUGHT BY TWENTY-FOUR-HOUR SERVICE

Next in evolution came the unexpected preponderance of the day load over the night load, with the necessity for expanding generating capacity for daylight rather than for nighttime service. It soon became obvious to the engineer devoting part of his time to central-station operation and part to the manufacture of electrical equipment that the designer's task had shifted from the production of better transformers to the design of better motors. The magnetizing current of the alternating-current motor became a far more important factor than that of the transformer had ever been. But the motor designer had nothing to offer.

William Stanley, one of the early industry's geniuses, attempted to market two-phase and three-phase motors with accompanying auxiliary static condensers, but the condensers were fragile. Section by section they broke down and the motor drifted back to its fundamental low power factor. The intention was good, but the result was to confirm the central-station world in its belief in the inevitability of low-power-factor motors.

In time came the rotary converter, and it was capable of offsetting, in the circuit as a whole, the bad effects of the poor power factor of motor load.

The conventional form of synchronous motor was also improved so as to be useful in the same way. My own company, about 15 years ago, proposed a unity-power-factor type of single-phase motor, but it was high in price compared with the conventional types; central-station rate schedules offered no inducement to its introduction, and it languished as a commercial product. The hunt for corrective means outside the motor, applicable to the circuit, resulted in the advent of the synchronous condenser, employed solely for power-factor correction.

But all these devices were only palliative. The power-factor problem has come down the years substantially unsolved. A number of operating engineers have cried out for relief, but the manufacturer of the chief offender—the alternating-current induction motor—has discreetly kept in the background, disclaiming responsibility and offering no solution. No wonder the central-station industry as a whole has slept upon the situation.

THE CHALLENGE TO MOTOR MANUFACTURERS

But when a business such as the electrical began to require unbelievable sums of money for expansion and realized that a very substantial percentage of all this capital was by-passing down the magnetizing-current chute; when it found the problem of uniformly good distribution service reaching staggering complexity, with this complexity tremendously magnified by the drag of heavy magnetizing currents for motors; when operating costs much in excess of the otherwise essential costs of production and distribution began to appear, it was not surprising that the time came when the National Electric Light Association demanded that the power-factor problem be solved.

In 1921 the Technical Section of the Association, at the Chicago convention, adopted a resolution recommending:

"That the incoming administration endeavor to have all induction motors hereafter manufactured compensated for lagging currents, this compensation to be capable of being varied to suit the loading conditions of a motor so that a power factor approaching unity may be obtained."

The incoming administration through H. L. Wallau, chairman of the apparatus committee, addressed the following letter to all motor manufacturers of the United States:

Dec. 12, 1921.

"Dear Sir: I have been instructed by the electrical apparatus committee of the National Electric Light Association to take up with the motor manufacturers the question of the production of alternating-current motors with high power factors at full and fractional loads.

"The subject is a vital one to the supply companies, the power factor of whose systems is gradually decreasing with increase of industrial loads, due to the large number of installations consisting of but a few motors of small capacity and generally operated well below rating.

"Because of their small size it is not commercial to install power-factor-metering devices on these average installations, and therefore a penalty clause for a low power factor cannot be applied.

"The only remaining remedy is to set a minimum power factor below which an installation will not be served. This means a tendency to slow up growth unless there are on the market in all sizes (motors) the use of which will meet the power company's requirements.

"As such a rule is seriously being considered by one of the largest companies and its enforcement in the near future is very probable, those manufacturers whose lines have been developed with high power factor in view will be in a fortunate position.

"Whether the improvement in power factor is to be obtained through change in present design, or by the use of present motors combined with static condensers, or through both, is, of course, a problem of the manufacturer.

"Nor is a gain of 1 or 2 per cent worth while. A preferable solution would be a combination of motor and condenser such that approximately unity power factor will be obtained over all ranges of load.

"Will you kindly direct the attention of your engineers to this subject and let me have your views on the matter not later than Jan. 9, 1922?

"Yours very truly,
H. L. Wallau,
Chairman Sub-committee on Motors, Electrical Apparatus Committee, National Electric Light Association."

This was indeed a challenge to the motor-producing branch of the industry. Some of the companies immediately placed emphasis upon the improvement of the conventional form of synchronous motor. Operating engineers began the much larger use of the synchronous condenser.

The company with which I am identified attempted to go to the principal source of the trouble—the induction motor itself—and see if it could not be made self-magnetizing. The Fynn-Weichsel motor, whose practicability is now definitely demonstrated, is the product of these investigations.

The engineers have now done their part and forced the method of a solution of the power-factor problem to the surface. The application is largely still to come. The devices essential to complete power-factor correction are at hand. The burden of solution is shifted from the manufacturer to the commercial division of the central station.

HOW A SOLUTION MAY BE EFFECTED

It seems to me as an interested onlooker that several moves are possible which will accelerate the solution.

1. Give up the effort to explain the phrase "power factor" to the public and follow C. F. Scott's recommendation, to talk "magnetizing current" only. It seems simple to explain to the central-station customer that the necessary supply of magnetizing current can be obtained on his own premises more efficiently and economically than by burdening the distribution system with its transmission, and that the cost of supplying it should be divided between the customer and the central station.

2. Formulate a sound principle of rate making which inherently places a premium on the reduction of magnetizing current on the customer's premises and eliminates all necessity for the discussion of bonus and penalty clauses. In other words, let the rate do the talking. A number of central-station commercial men have expressed the opinion that a kilovolt-ampere rather than a kilowatt demand rate has at least great possibilities.

3. Is it not a principle that could and should be established that the central union cannot permit the magnetizing current to interfere with good service to adjacent customers? It seems that if it is logical to rule off heavy starting currents which temporarily disturb good regulation of the system, it is equally logical to rule off heavy magnetizing currents which continually impair good regulation.

4. Cannot all parties interested in the problem agree that the capital cost of elimination of magnetizing current belongs in part to the customer, because (*a*) he will reap advantages in internal improvement of plant operation, and (*b*) an investment obligation rests upon him to prevent the interference of his load with service to other central-station customers in the immediate neighborhood; and in part to the central station, because (*c*) elimination of magnetizing current reduces the capital investment per kilowatt of energy sold, (*d*) greatly reduces the energy losses in distribution, and (*e*) reduces the cost of maintaining good system regulation?

I recently heard a central-station executive put his views on the problem in about the following words:

"We've been talking about this power-factor problem for a long time. I'm going to find out just what it is. We've got some of this 'magnetizing' current on our system. How much? A certain amount of our capital investment is non-productively employed in carrying this magnetizing current. How much? We're losing a certain amount of energy in our distribution system in distributing this magnetizing current. How much?

"They tell me that we can give better service to the public if we get rid of this magnetizing current. In what ways, and how much better? I'm going to ask my engineers for the facts in hard, cold figures in respect to our system, and if they're as bad as some of you gentlemen say, and the possibilities of better service as important as you say, we're going to get busy and get rid of this power-factor problem on our system."

Such a spirit will soon set the pace in the industry, and as it becomes common, a few more years will see the problem dead and buried.

36. L. W. W. Morrow.[1]

The effects of low power factor on the operations of the electrical industry have been discussed for many years and much experience in the institution of corrective measures has been had. Yet on an industry-wide scale the evils associated with low-power-factor conditions become greater each year, even though the incentives for the institution of corrective measures increase. Low power factor has come to be recognized as the major handicap to better and more efficient electric service, and men of the industry are striving actively for a commercial and engineering method for its correction.

HIGH-POWER-FACTOR OPERATION IMPROVES SERVICE

An analysis of the data and experiences of those properties which have instituted power-factor correction leads to the conclusion that operation under high-power-factor conditions improves both the quality and the efficiency of the service rendered by the utilities and used by their customers. Correction of power factor has its greatest influence in improving the voltage regulation and through this action enables the utility to give better service and the customers to secure better use of the service. Secondary gains resulting from power-factor correction consist of the release of system capacity with a consequent reduction in investment and a reduction in system losses with a resultant reduction in operating charges. Thus correction tunes the system and makes it cheaper and easier to give service of the quality desired in modern industry.

Actual experience shows that power-factor correction can be instituted successfully as a part of the business activities of light and power companies and as a part of the normal operating activities of industrial users of electricity. It does not require an elaborate or costly departure from customary business activities, and it secures returns to the producer and user the value of which is tangible and worth while. Yet little actual progress in power-factor correction can be seen because of many obstacles, mostly imaginary, set up in the minds of executives and customers.

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[1] Managing editor, *Elec. World*. "Power-factor Correction," abstract in *Elec. World*, vol. 61, p. 435, 1925, from a paper presented at Regional Meeting, District No. 2, American Institute of Electrical Engineers, Washington, D. C., Jan. 23–24, 1925.

The fact is that many properties have instituted correction successfully and made it a profitable part of their business. They have done this without any difficulty and did not find any great complexity or major changes introduced in their operating routine. Thus the time is ripe and the methods are available for eliminating low-power-factor conditions in the electrical industry. The rewards are ample, and the necessity for this move becomes greater with the growth of electrical systems.

LOCATION OF CORRECTING EQUIPMENT

A study to determine the locations in which to install corrective equipment on existing systems shows the decision is somewhat influenced by the type of system and by local conditions. Usually, corrective equipment should be located at all low-power-factor loads, in some cases at substations at a distance from generating stations, particularly if voltage regulation is desirable, and in a very few instances at the generating stations. The source of low power is at the load, and analysis will show that corrective equipment is best and most economically used in location.

CONSUMER CORRECTION

The analysis for determining the proper location of corrective equipment leads inevitably to the conclusion that most of it should be placed on the premises of consumers and that consumers using high-power-factor equipment are operating most economically from their own viewpoint and from that of the central station. From the angle of the central station, correction relieves the system of the necessity for correction at other locations, releases the transformer and cable capacity where it is most valuable from income and load-factor viewpoints, reduces losses where they are greatest, and improves regulation where it is most desirable to have good regulation.

From the angle of the consumer, correction of his own equipment or the replacement of low-power-factor equipment will secure several tangible and intangible results. It will reduce the losses inside his premises, for which he pays a high rate; it will improve his voltage regulation and reduce his voltage drop, so that his machinery will operate faster and more smoothly; it will give him better-quality production, better lighting, fewer rejections of manufactured product, faster machine-starting conditions and secure for him a direct decrease in his power bill if he buys under a proper rate system.

Experience shows that operating complexity is not increased and that the industrial plant corrected for bad power-factor conditions reaps decided tangible and intangible benefits. Needless to say, it is useless to attempt an itemized cost evaluation for correction at load locations, because the complexity of modern distribution systems, the variety of loads and services, and the many assumptions necessarily make all combine to give inaccurate results. In a broad way, however, based on the actual cost of the distribution system, the cost of voltage regulation and the cost of losses, an analysis in dollars will show decided inducements for investing power-factor correction at the source.

KINDS OF CORRECTIVE EQUIPMENT

The corrective equipment to install at locations decided upon is determined largely by each local situation, but there are applications for all available types of low-power-factor loads, such as:

1. The synchronous motor.
2. The synchronous condenser.
3. The high-power-factor commutating motor.
4. The static condenser.

Investment charges on existing installations, production requirements, fixed and operating charges on corrective equipment, and the skill required to operate the equipment influence the decision to be made for each load considered.

POWER-FACTOR RATES THAT HAVE BEEN USED SUCCESSFULLY

The ultimate approach to power-factor correction for customers is by means of rate making. This has generally taken the form of:

1. The use of power-factor clauses.
2. The use of kilovolt-ampere demand clauses.
3. The use of kilovolt-hour clauses.
4. A combination of two of the foregoing.

All of these methods have been used and all have worked more or less successfully, but all are subject to definite criticisms. Years of effort proved the impossibility of developing utility rates on a cost-of-service basis, and, however reluctantly, rate makers have admitted its impossibility and impracticability for modern conditions of utility service. No cost-of-service basis can be found, therefore, for making any type of power-factor rate, and each property must solve a rate that can be instituted and operated to suit conditions encountered. A fundamental in power-factor rate making would be to secure a simple rate, one that could be applied to all customers, one that needed little maintenance or supervision, and one that offered a financial inducement to customers to maintain and correct power-factor conditions.

Every type of power-factor rate has been used successfully; so the necessity of a rate to secure power-factor correction is not a real obstacle to the institution of correction. It must be remembered that grand average results only are to be expected and that precision methods and analyses must be modified by commercial considerations of each power system.

POWER-FACTOR CORRECTION IN PRACTICE[1]

"Power-factor correction has been talked about for many years; yet little progress has been made on a national scale. In fact, there seems to be a diminution of interest in the subject just now. You have studied the question for years. Do you think that power-factor correction is worth while, and can you explain why it has not been attempted more generally by central-station companies?"

These questions were asked of Charles J. Russell, vice-president of the Philadelphia Electric Company, a nationally recognized authority, who has long studied the possibilities of power-factor correction and has instituted it very successfully on the system of the Philadelphia Electric Company.

"Power-factor correction is the one major economic opportunity remaining in the light and power industry," replied Mr. Russell. "It affords great possibilities for economic gains in industry as a whole and splendid opportunities for improving service and operating conditions. And, in answer to your other question, I believe it has made little progress because it has not received serious consideration from many executives in the light and power industry. It has been a vague conception in their minds and has encountered the inertia associated with the activities of a flourishing industry."

"But," interposed the interviewer, "it is said that technical, financial, public relations and commercial considerations make it difficult to institute power-factor correction as a part of the practical operations of a power system. The selection of the proper type and quantity of corrective equipment, the education of customers, the cost and the inadequacy of metering equipment and methods, the difficulty of handling investment charges, the task of making rates satisfactory to customers and regulatory bodies—all these elements are said to be great obstacles. In other words, it is said that the economic gains to the power customers and to the utilities are impossible to obtain in practice."

"That's all nonsense," replied Mr. Russell energetically. "We have done the job successfully on this system, and it has paid big returns to the customers and to ourselves. The difficulties you mention melt away, provided an intelligent study is made of system conditions, and power-factor correction is applied properly. It is fundamental that the customer as well as the utility shall benefit financially, and that is the key to the whole situation. We have no trouble of any character on this system and have ample data to show that power-factor correction is both possible and profitable."

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[1] These excerpts are taken from an article by L. W. W. Morrow of this title which appeared in *Elec. World,* vol. 84, p. 1,096, 1924.

In reply to Mr. Morrow's question, "What do you think of the possibilities of power-factor correction?" J. F. Gaskill of Mr. Russell's department replied, "To tell you the truth, I am pretty tired talking about power-factor correction, for it has been settled on this system and in my mind so long that it has become an old story. Power-factor correction is working splendidly on this system. It gives us no trouble, takes very little time, and involves very little expense. It pays us and it pays the customers. We have about 24,000 corrective kva. on customers' premises, of which about 4,000 kva. is in static condensers and the remainder in synchronous machinery. At first we gave a lot of time and study to the question and carefully tested plants and scrutinized all power bills. But that period is passed and everything has been reduced to routine."

"But how do you care for billing and how do you get corrective equipment installed?" was asked.

"Our wholesale power rate," he replied, "is based on tests made under normal operating conditions in a plant. This gives data for fixing kilowatt and kilovolt-ampere demand limits and determines the power-factor charges to be applied under the contract. We make about two hundred such tests a year, and the average cost of each test is less than $6. Once the contract is signed, routine billing is made from the readings of a polyphase watt-hour meter and a kilowatt demand meter installed on the customer's premises. Naturally, if the test kilovolt-ampere demand is high compared with the kilowatt demand, we tell the customer that power-factor correction will reduce his bill."

CHAPTER VII

FUNDAMENTAL PRINCIPLES OF THE POWER FACTOR AND ITS CORRECTION

Only the underlying principles herein are considered, and in a simple manner. An induction motor having a low power factor is out of tune. To obtain the maximum power factor, tune it by adjusting the capacity of a condenser or its equivalent to the inductance of the motor, and the power factor will become higher the closer the tuning becomes. The induction motor is not tuned to the natural frequency of the circuit when working independently. The application of a condenser of some sort acts in a manner similar to the condenser in a radio set. Simple explanations of some of the characteristics of induction motors are given, and the effects of applying power-factor-corrective apparatus and the reasons therefor are shown.

37. Some Fundamental Alternating-current Principles.—The flowing electricity constituting the magnetizing current possesses inertia just like matter. When voltage is applied exclusively to this magnetizing electricity, time is required to set it in motion. Once set in motion, the magnetizing electricity tends to remain in motion without any force of any kind acting to keep it moving. The alternating voltage does not start to set the magnetizing electricity in motion until this voltage has attained its maximum value, and it acts to set the magnetizing electricity in motion only while it is decreasing from its maximum value to zero. Hence, the strength of the magnetizing current is equal to zero when the voltage exclusively acting on the magnetizing electricity is a maximum, and the magnetizing current strength is a maximum when the voltage producing it is equal to zero. During the entire quarter cycle ($\frac{1}{240}$ sec. when the frequency is 60 cycles per second) that the voltage is falling from a maximum value (either positive or negative) to zero, it is setting the magnetizing electricity in motion, that is, accelerating it, and then the voltage reverses and tries to stop the motion of the magnetizing electricity, but it cannot completely do so until the voltage has again attained its maximum value in the reverse direction.

When the supply voltage is thus employed exclusively in alternately moving and stopping the magnetizing electricity, there is no running current at all, in which case the reactance drop would be 100 per cent. But there is always some electric resistance present and motors are usually running when voltage is applied at their terminals; so running current is always present with magnetizing current and the voltage opposing the supply voltage can never be entirely reactive. The object of power-factor correction is to make the major portion of the voltage and the current active for running motors, producing light, and so forth.

A static condenser acts like an electrically elastic diaphragm. Connecting the proper size of static condenser across the terminals of an induction motor is like tuning a radio set so that the maximum amount of working current may be obtained for a given total current strength. The discharge of the magnetic energy from the induction motor (comparable to an inductance coil) is caught by the condenser and again returned to the motor to magnetize it as the current reverses. The more nearly an induction-motor-and-condenser combination is tuned to the frequency of the power circuit, that is, the closer the natural frequency of the above or similar combination approaches the frequency of the power circuit, the closer will the power factor approach unity, or 100 per cent. It is comparable to adjusting the hair spring of a watch to the inertia of the balance wheel so that the oscillatory motion shall be correctly tuned to make the watch "keep time."

In an incandescent lamp, about all of the electric energy is converted into heat through the friction of the moving electricity with the structure of the filament; so the voltage and the current it produces are in step or in phase at all times, because the drag on the electricity due to its friction with the structure of the filament prevents its moving any further after the voltage becomes equal to zero. Hence, as the voltage acts first in one direction and then in an opposite direction, the direction of the current reverses at substantially the same instant that the voltage reverses. Thus, the voltage becomes equal to zero at the instant its direction reverses, the electricity comes to a standstill during the same instant, the power factor is unity, and the current strength is always directly proportional to the supply voltage at any instant (Ohm's law).

But when the voltage opposing the supply voltage is all lagging reactive, due to some inductive device, as a reactor the supply voltage is substantially a maximum when the current strength is equal to zero, and the circuit is entirely out of tune. Then the total current (now all magnetizing current) is said to lag behind the supply voltage by one-quarter cycle, or 90 electrical degrees, as indicated in Fig. 17*a*, wherein the arrows or vectors at the left revolve in the direction shown to produce the sine curves or sinusoids at the right.

In what follows, the horizontal axis at the left is always[1] the axis of the working current and the supply voltage, or the axis of power in kilowatts.

In Fig. 17*a* the supply voltage is 90 deg. ahead of the total current (now all magnetizing current) when they are said to be in quadrature, and the power factor is equal to zero since there is no working current.

It will be noted that the lagging reactive kilovolt-amperes, or the various products of the instantaneous and corresponding values of the supply voltage and the lagging magnetizing current, are alternately negative and positive and, therefore, have no value whatever as a continuous energy supply for any even number of half cycles, since the positive and negative values cancel out. The frequency of the kilovolt-amperes is double that of the voltage and current in all cases.

Figure 17*b* is similar to Fig. 17*a* with the exception that the current is leading instead of lagging, and represents the effects produced by connecting a static condenser to the source of supply voltage. The reactive kilovolt-amperes in Fig. 17*b* exactly oppose those in the case of Fig. 17*a*, the values being expressed in per cent. There is no working current in either case, only magnetizing current being present; so the power factor is equal to zero in both cases.

In Fig. 17*c* the power factor is unity, or 100 per cent, because the supply voltage and the total current are in phase. Hence, the total current is all working current, and there is no magnetizing current present. This condition may be obtained with a lamp or resistance heating load, or by making the two reactive kilovolt-amperes exactly oppose each other. It will be noted

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[1] This is a departure from the conventional method of vector representation, "lagging" here meaning "below the horizontal axis," and "leading" meaning "above the horizontal axis," but it is believed it will more readily be grasped by those for whom it is intended, and engineers familiar with vectors will understand it at any rate.

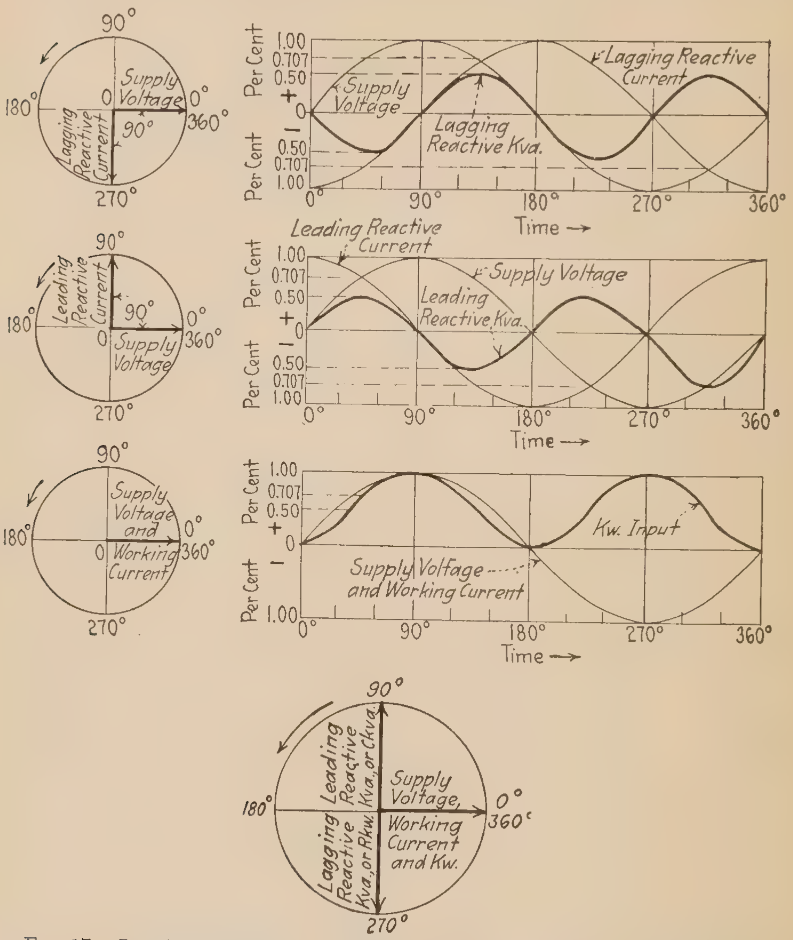

FIG. 17.—Lagging, leading and in-phase currents. *a.* Current lagging 90 deg. behind the supply voltage. *b.* Current leading the supply voltage by 90 deg. *c.* Current in phase with the supply voltage. *d.* Vectorial representation.

that the kilovolt-ampere waves are now kilowatt waves, since they are all positive and, therefore, do not cancel out.

When any of the current strengths in Fig. 17 are multiplied by the voltages or kilovolts, all vectors represent volt-amperes or kilovolt-amperes. This is illustrated in Fig. 17*d*, wherein a condition of resonance (or "tuning") is assumed, the lagging reactives being neutralized by the leading reactives so that the power factor is unity, there is no magnetizing current outside of the combined reactive devices, and the line current is all working current. Within the two reactive devices, however, the magnetizing current is the same as usual. This in one principle of correcting the power factor by supplying magnetizing current at or near the device requiring it.

The term, "reactive kilowatt," represents the lagging reactive quadrature component of the total kilovolt-amperes due to the inductive device. This corresponds to the readings of reactive kilowatt-hour meters when the readings are divided by the number of hours of measurement. Hence, reactive kilowatts (rkw.) means lagging reactive kilovolt-amperes.

The term "kilowatt (kw.)," is the in-phase or motor-running and heating component of the total kilovolt-amperes and is always in phase with the supply voltage.

The term, "corrective kilovolt-ampere (ckva.)," is the leading reactive quadrature component of the total kilovolt-amperes due to a power-factor-corrective device, as a static condenser.

The total kilovolt-amperes are not shown in Fig. 17. The total kilovolt-amperes magnetize and run motors and produce heat. In the foregoing, only the in-phase or power component and the quadrature or reactive components are explained. The total kilovolt-amperes are equal to the square root of the sum of the squares of the difference in the reactive components and the in-phase component.

The magnetizing current is a part of the quadrature kilovolt-amperes, while the running current is a part of the in-phase kilovolt-amperes, or kilowatts.

Only the effective values are used in general alternating-current calculations. One effective ampere, with the proper voltage producing it, is that which will cause the production of heat at the same time-rate as one ampere of direct current. One effective volt will produce a current strength of one effective ampere in a circuit having a resistance of one ohm. Consequently, when the supply voltage is constant, the phases are balanced, and the wave form is sinusoidal; the continued product of the supply voltage across any two wires at the motor terminals, the number of amperes in any wire (except in three-wire, two-phase systems), and a constant number gives the total kilovolt-amperes for the motor.

For a single-phase circuit,

$$\text{kva.} = \text{volts} \times \text{amperes}/1{,}000.$$

For a balanced two-phase circuit,

$$\text{kva.} = 2 \times \text{volts} \times \text{amperes}/1{,}000.$$

For a balanced three-phase circuit.

$$\text{kva.} = 1.732 \times \text{volts} \times \text{amperes}/1{,}000.$$

The phase angle θ (Greek letter *theta*) is the angle by which the total effective current lags behind the supply voltage when the power factor is lagging, as when only an idle transformer or an underloaded induction motor is connected to the source of supply, or leading when the power factor is leading, as when only a condenser of some form is connected to the source of supply. The phase angle θ may be either positive or negative. When the power factor is equal to zero, the phase angle may be either +90 deg. or −90 deg. When the power factor is unity, the phase angle is 0 deg. and the total current is in-phase or working current.

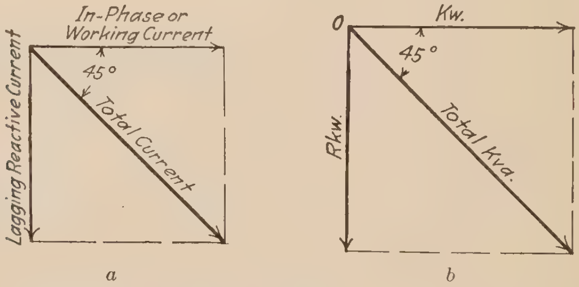

Fig. 18.—Relations of the total components to the quadrature components. *a*. Current relations. *b*. Kilovolt-ampere relations.

Figure 18*a* shows the relations of the total current to its quadrature components, while Fig. 18*b* illustrates the relations of the total kilovolt-amperes to its quadrature components when the current is lagging. The conditions for leading currents and kilovolt-amperes are similar but inverted. The phase angle θ is 45 deg., lagging, in both cases.

When the effective values are employed, as in the foregoing, the instantaneous values of alternating current and voltages may be neglected entirely, although it is well to remember that the maximum values of the current strengths and voltages are about 1.4 times the effective values.

From the foregoing:

1. When the total current lags 90 deg. behind the supply voltage, the power factor is equal to zero and the number of active kilowatts is equal to zero; the entire number of kilovolt-amperes being lagging reactive and herein termed reactive kilowatts.

2. When the total current and the supply voltage are in phase, the power factor is equal to unity, or 100 per cent (the condition for Ohm's law), and all of the kilovolt-amperes are active and useful for running motors and producing heat, and are equal to the number of kilowatts.

3. All lagging power factors fall between the two extremes, and a portion of the total kilovolt-amperes is active (kw.) while the other portion is lagging reactive (rkw.).

4. Synchronous machinery, static condensers, and Fynn-Weichsel motors possess sufficient leading reactive kilovolt-ampere (ckva.) capacity wholly or partly to balance the lagging reactive kilovolt-amperes (rkw.) in induction motors and the like.

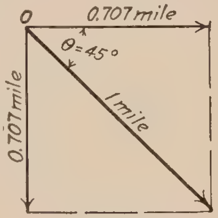

Fig. 19.—Relation of actual travel to its quadrature components.

38. The Problem of the Mariner.—The meaning of the conditions shown in Fig. 18 may be illustrated by the following analogy, as in Fig. 19.

Suppose an attempt is made to sail a ship directly eastward, but winds and currents also force it southward. If, during a given time interval, it travels 0.707 mile eastward, that is, in the direction in which it is desired to sail, but also goes southward, that is, in a direction in which it is *not* desired to sail, and over a distance of 0.707 mile in the southward direction during the same time interval, then the ship will travel in the southeast direction, and the length and angular position of the arrow (vector) show the actual relative distance and direction in which the ship travels during the same time interval.

The distance the ship moves southeasterly is equal to the geometric sum (square root of the sum of the squares) of the eastward and southward distances over which the ship moves during the same time interval, or to

$$\sqrt{0.707^2 + 0.707^2} = \sqrt{0.50 + 0.50} = 1.$$

Hence, the ship moves 1 mile southeasterly while it simultaneously moves 0.707 mile eastward and 0.707 miles southward.

If the ship continued thus to sail for an indefinite period of time, the relations would never be changed; that is, for every mile it sailed southeasterly, it would sail 0.707 miles eastward and 0.707 mile southward. If it sailed 1,000 miles southeasterly, it would sail 707 miles eastward and 707 miles southward. Under these conditions, it would sail at an angle of 45 deg. southward of the horizontal eastward line.

Hence, when the length of the radius or vector is equal to 1 and it is displaced 45 deg. from the horizontal line, the corresponding horizontal value is 0.707 and the corresponding vertical value is 0.707.

The horizontal values are the cosines of the phase angle θ, or $\cos \theta$, while the vertical values are the sines of the phase angle θ, or $\sin \theta$, when the length of the radius is taken as 1. For any other length of radius or vector, divide the horizontal and vertical values by the value represented by the corresponding length of the radius or vector. The results are $\cos \theta$ and $\sin \theta$, respectively. Figure 20 shows the relations.

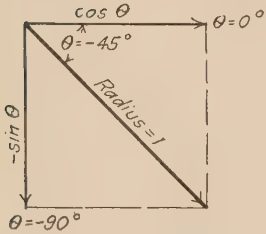

FIG. 20.—Relation of radius to its quadrature components, sin θ and cos θ. Sin θ is here negative because it is lagging.

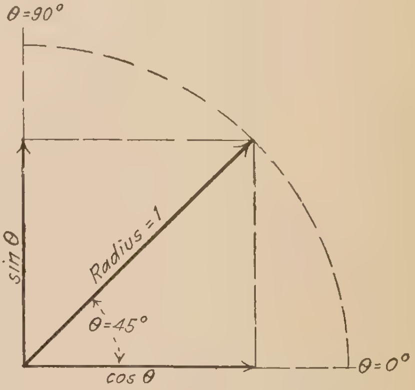

FIG. 21.—Reversed conditions.

39. Correcting the Course.—If the mariner knew the conditions of wind and current beforehand, he would lay out his course northeastward, as in Fig. 21. The course that would be traveled if he steered due east (and actually traveled southeast) and the course he lays out to offset these effects so that he can travel due east, are illustrated in Fig. 22, wherein the sines and cosines of the phase angle $\theta = 45$ deg. are inserted. The net result is that the phase angle θ now becomes 45 deg. − 45 deg. = 0, and sin θ becomes equal to $0.707 - 0.707 = 0$; that is, the two radii in Fig. 22 swing together and merge as a single radius. The effect is to make cos θ maximum, which is 1, or 100 per cent, as indicated in Fig. 23.

40. Navigating the Motors.—Cos θ, the power factor, always lies on the horizontal axis in the above diagrams. Sin θ, the reactive or quadrature component, always lies on the vertical axis. The maximum value of each is 1, or 100 per cent, and the minimum value of each is 0. When sin θ is negative or lagging, cos θ is lagging. When sin θ is positive or leading, cos θ is leading. When sin $\theta = 1$, cos $\theta = 0$, and all of the kilovolt-amperes are reactive. Under this condition, there would be no running current for a motor. When cos $\theta = 1$, sin $\theta = 0$, and all of the kilovolt-amperes (kw.) are useful to drive motors and produce heat, provided the motors are of the self-magnetizing class.

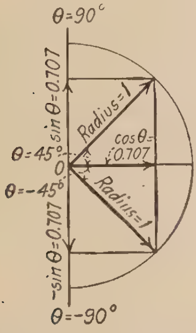

Fig. 22.—Neutralizing effect.

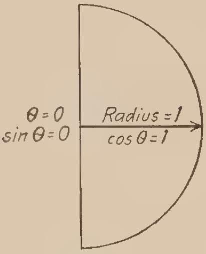

Fig. 23.—Cos θ a maximum through neutralization.

The magnetizing current of an induction motor does not vary greatly with the load at constant voltage, as a general rule; so sin $\theta \times$ kva. = rkw. remains quite constant, increasing somewhat with the load, although it increases more in some motors than in others. It is the increase in the working current as the motor is loaded that increases the power factor in induction motors, since the total current does not increase so rapidly as the working current when the load on the motor is increased.

Static condensers and other apparatuses for improving power factors have leading kilovolt-amperes when connected to a line. When the phase angle θ for both the power-factor-improving apparatus and the induction motor are the same but have different signs, and the two are connected close together across a branch or main, the power factor of the combination becomes 1, or 100 per cent, because the power-factor-improving apparatus absorbs the lagging reactive kilovolt-amperes (rkw.) discharged from the induction motor and then sends it back to the motor to again magnetize it, as described in Art. 6.

This phase of the power-factor-waste problem is very similar to the mariner's problem in that the vector representing the entire magnitude and direction of the total kilovolt-amperes should be as close to the horizontal axis (that is, it should lie in the horizontal plane) as may be practicable, so that most of the total kilovolt-amperes may be in the form of kw. and thus be useful for running motors. Loading the induction motors often does this quite satisfactorily, but when power-factor-improving apparatus is applied to a motor, the course laid out for the total kilovolt-amperes is upward and to the right. The nearer the sin θ of this course approaches that of the sin θ (with opposite sign) of the motor characteristics, the nearer will the phase angle θ of the motor and power-factor-corrective apparatus in combination approach zero and the nearer will the power factor (cos θ) approach unity.

Figures 22 and 23 apply equally to the mariner's problem and the problem of improving the power factor, cos θ, by external means.

41. Relations Involving the Phase Angle θ.—Table VIII shows the abbreviations and the relations of some of the trigonometric functions usually found in tables thereof.

The expression for the power factor is cosine θ, written cos θ, pronounced "cosine *theta*," and meaning "cosine of the phase angle *theta*."

The relations in Table VIII are plotted in Fig. 24, and may be verified by consulting a table of trigonometric functions, remembering that the radius is assumed to be unity.

TABLE VIII.—ABBREVIATIONS AND RELATIONS OF SOME TRIGONOMETRIC FUNCTIONS

Function of angle θ	Abbreviated expression	Relations
Sine....................	$\sin\theta$	$= \dfrac{\cos\theta}{\cot\theta} = \cos\theta \times \tan\theta$
Cosine..................	$\cos\theta$	$= \dfrac{\sin\theta}{\tan\theta} = \sin\theta \times \cot\theta$
Tangent................	$\tan\theta$	$= \dfrac{\sin\theta}{\cos\theta} = \dfrac{1}{\cot\theta}$
Cotangent..............	$\cot\theta$	$= \dfrac{\cos\theta}{\sin\theta} = \dfrac{1}{\tan\theta}$

The relations between $\sin\theta$, $\cos\theta$, $\tan\theta$, and $\cot\theta$, for both positive and negative values in some cases, are shown in Fig. 25, which should be compared with Fig. 22. The angles in Fig. 25 are made different from those in Fig. 22 so as to make the relations of $\tan\theta$ and $\cot\theta$ clearer. The absence of the sign + means that the quantity is positive just the same. The data are:

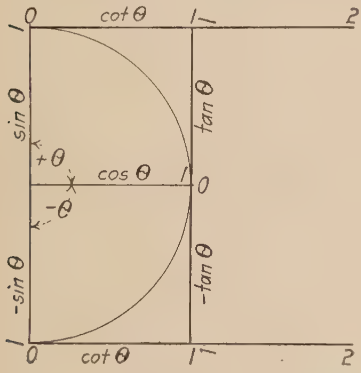

FIG. 24.—Relations of trigonometric functions.

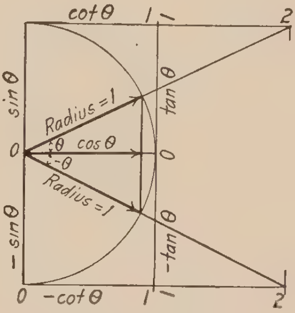

FIG. 25.—Modification of Fig. 22.

$\theta = 26$ deg. 34 min.
$-\theta = -26$ deg. 34 min.
$\sin\theta = 0.447$
$-\sin\theta = -0.447$

$\cot\theta = 2.00$
$-\cot\theta = -2.00$
$\tan\theta = 0.500$
$-\tan\theta = -0.500$
$\cos\theta = 0.894$

When the two radii are swung together so as to coincide with the horizontal axis, the following occurs: $\theta = 0$, $\tan\theta = 0$, and $\cot\theta$ increases to infinity. But what happens to $\cos\theta$, the power factor? It simply increases to unity, or 100 per cent. Sin θ decreases to zero, but $\cos\theta$ is increased to 1.

If the two radii were equally separated from the horizontal axis so as to coincide with the vertical axis, each would be displaced by 90 deg. from the horizontal axis, $\sin\theta$ would be equal to 1 and $-\sin\theta$ would be equal to -1, but they would cancel out; so the net value of $\sin\theta$ would be 0.

42. Relations of Some Trigonometric Functions to Electrical Quantities.—Table IX is similar to Table VIII, but it also shows the relations of the electrical quantities to those in Table VIII.

TABLE IX.—SOME TRIGONOMETRIC AND ELECTRICAL RELATIONS

QUANTITY	VALUES
Kw.	$\cot\theta \times$ rkw., $\frac{\text{rkw.}}{\tan\theta}$, $\cos\theta \times$ kva.
Rkw.	$\frac{\text{kw.}}{\cot\theta}$, $\sin\theta \times$ kva., $\tan\theta \times$ kw.
Kva.	$\frac{\text{kw.}}{\cos\theta}$, $\frac{\text{rkw.}}{\sin\theta}$.
Sin θ	$\frac{\text{rkw.}}{\text{kva.}}$, $\tan\theta \times \cos\theta$, $\frac{\cos\theta}{\cot\theta}$.
Cos θ	$\frac{\sin\theta}{\tan\theta}$, $\sin\theta \times \cot\theta$, $\frac{\text{kw.}}{\text{kva.}}$, power factor.
Tan θ	$\frac{\text{rkw.}}{\text{kw.}}$, $\frac{\sin\theta}{\cos\theta}$.
Cot θ	$\frac{\text{kw.}}{\text{rkw.}}$, $\frac{\cos\theta}{\sin\theta}$.

The relations in Table IX are graphically represented in Fig. 26.

Before any calculations can be made, one of the functions of θ (as $\cos\theta$) and kw., kva., or rkw. must be known in such combinations that the remaining quantities may be computed.

Example: Given $\theta = 26$ deg. 34 min., and kva. = 230. Reference to a table of trigonometric functions shows that for $\theta = 26$ deg. 34 min., $\cos\theta = 0.894$, $\tan\theta = 0.500$, $\sin\theta = 0.447$, and $\cot\theta = 2.00$. Hence, kw. = $\cos\theta \times$ kva. $= 0.894 \times 230 = 206$, as the kilowatt input required to run the motor, while rkw. = $\sin\theta \times$ kva. $= 0.447 \times 230 = 103$ is the lagging reactive kilovolt-amperes of the motor.

43. Three Ways to Improve the Power Factor.—The power factor of a squirrel-cage induction motor alone can be improved only by increasing the load on the motor. In no other way can the power factor of such a motor alone be improved. By comparison with the problem of the mariner, the latter might spread more and more sail to increase his eastward travel, but he could never sail due east by so doing. Likewise, while the power factor of an induction motor should always be increased to as near its full-rated-load limit as practicable, the power factor of the motor can never be increased to 100 per cent by so loading it.

The power factor of an induction motor can never be increased by means of power-factor-improving apparatus connected in the circuit with it in whatever manner. The power factor of the motor stays right where it was. There is just as much magnetizing current as before. What is improved is the power factor of the motor and the power-factor-improving apparatus in combination. It would be a foolish mariner who would not steer northward to correct his course to eastward without spreading all sail practicable.

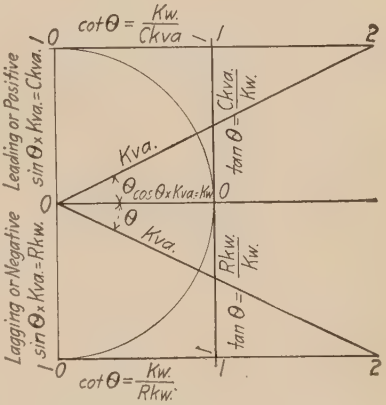
$\cot\theta = \frac{Kw.}{Ckva}$
0
1
2
Leading or Positive
$\sin\theta \times Kva. = Ckva.$
1
$\tan\theta = \frac{Ckva.}{Kw.}$
Kva.
θ
$\cos\theta \times Kva. = Kw.$
0
0
θ
Kva.
Lagging or Negative
$\sin\theta \times Kva. = Rkw.$
$\tan\theta = \frac{Rkw.}{Kw.}$
1
0
1
2
$\cot\theta = \frac{Kw.}{Rkw.}$

Fig. 26.—Relations of electrical quantities and trigonometric functions.

However, the plant power factor may be improved in three ways:

1. By loading the induction motors as much as practicable, using smaller motors where the larger ones cannot be properly loaded.
2. By using power-factor-corrective apparatus to supply magnetizing current.
3. By using large resistance heating loads, as resistance furnaces, ovens, and the like, to increase the total kilovolt-amperes without increasing the magnetizing current. It is suggested that many plant power factors are higher than they would be if there was not so much heating of wires and cables in the distribution system.

CHAPTER VIII

SOME CHARACTERISTICS OF INDUCTION MOTORS

In his discussion of a paper by H. Weichsel at the Midwinter Convention of the A. I. E. E., 1925, Prof. C. F. Scott stated:

> It happened to be my lot to be associated with Mr. Tesla in his early work in the development of his polyphase motor. I remember very well his statement that his motors were of two kinds: the synchronous motor, a splendid motor to run; and the induction motor, which he called a torque motor, that would start.

The information given in the present brief chapter is of an elementary nature and is intended only to explain the principles of the power-factor characteristics so that the practical information contained in the following chapter may readily be understood.

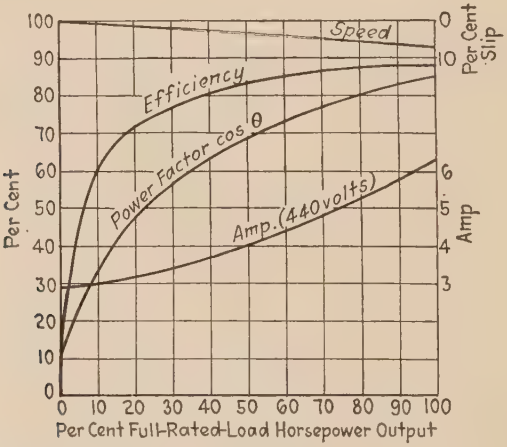

FIG. 27.—Some characteristics of a 5-hp., 440-volt, 60-cycle, squirrel-cage, polyphase induction motor.

44. General Characteristics of Squirrel-cage Polyphase Induction Motors.—In Fig. 27 are shown some characteristics of a commercial 440-volt, 60-cycle, 5-hp., squirrel-cage, polyphase induction motor. It is to be noted that the motor is here

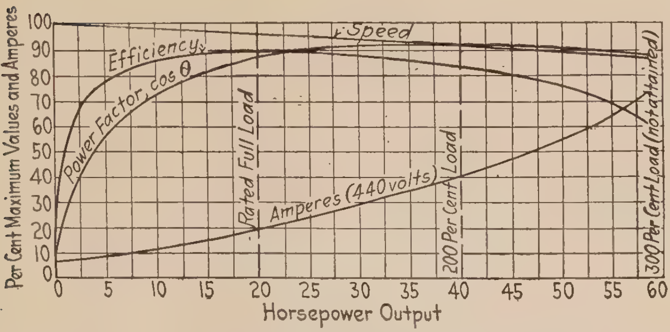

Fig. 28.—Overload characteristics of a 20-hp., 440-volt, 60-cycle, squirrel-cage, polyphase induction motor.

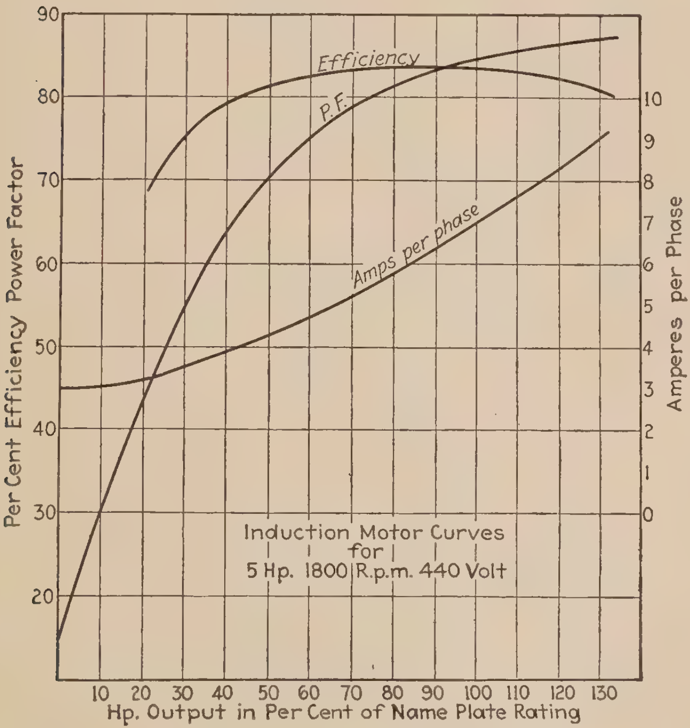

Fig. 29.—Characteristics of a 5-hp. induction motor.

started without load, and that the starting current under this condition is slightly less than 3 amp. The various data are plotted against the horsepower output. It is shown further on that such data really should be plotted against the kilowatt input. It also will be noted that while the efficiency is equal to zero at no load, the power factor has a definite value at zero load, but the percentages tend to become equal to one another

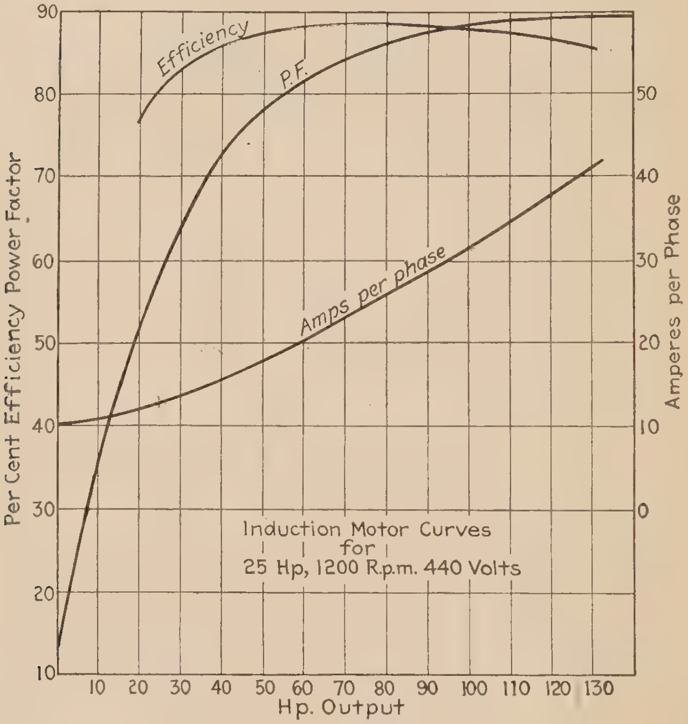

FIG. 30.—Characteristics of a 25-hp. induction motor.

at the full rated load of the motor. The per cent synchronous speed of the motor falls from about 100 per cent at zero load to about 93 per cent at the full-rated-load output of the motor. The difference between 100 per cent synchronous speed and any other percentage of synchronous speed is the slip. Hence, in Fig. 27, the full-rated-load slip of the motor is about 7 per cent.

The 440-volt, 60-cycle, 20-hp., squirrel-cage, polyphase induction-motor characteristics in Fig. 28 are quite similar to those in Fig. 27, up to the full-rated-load capacity of the motor, but the characteristics are extended beyond the full-rated-load values, the maximum horsepower output being approximately 57 hp., at which load the motor pulls out; that is, it stalls, and ceases to run. The pull-out torques of such motors usually are taken as about two and a half times those of the full-rated-load torques. These general characteristics are common to all squirrel-cage polyphase induction motors, although the values vary.

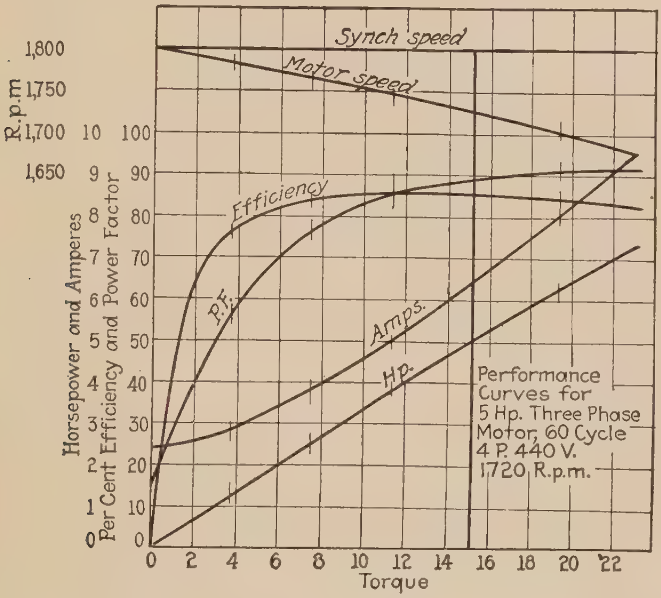

FIG. 31.—Characteristics of a 5-hp. induction motor plotted against torque.

Again referring to Fig. 28, it will be observed that when the motor is overloaded, the power factor increases up to a certain point but the efficiency decreases.

Figures 29 to 34 show further characteristics of induction motors.

45. Efficiency and Kilowatt Input.—The equation for the efficiency of a motor is:

$$\text{Efficiency} = \frac{\text{horsepower output} \times 0.746}{\text{kilowatt input}} = \frac{\text{mechanical kilowatt output}}{\text{electrical kilowatt input}}.$$

Therefore, horsepower output = 1.341 × kilowatt input × efficiency,

$$\text{and} \qquad \text{kilowatt input} = \frac{\text{horsepower output} \times 0.746}{\text{efficiency}}.$$

There are 1.341 hp. in 1 kw., and 0.746 kw. in 1 hp.

46. The Kilowatt Input as the Basis of Measurement.—The power factor is the ratio of the kilowatt input to the total kilovolt-amperes. Hence, the kilowatt input must be determined from the horsepower output, as in the preceding article, before any definite procedure can be made. Furthermore, all data should be plotted against the kilowatt input rather than against the rated horsepower output, because of the efficiency and the number 0.746. Hence, for a 5-hp. output and an efficiency of

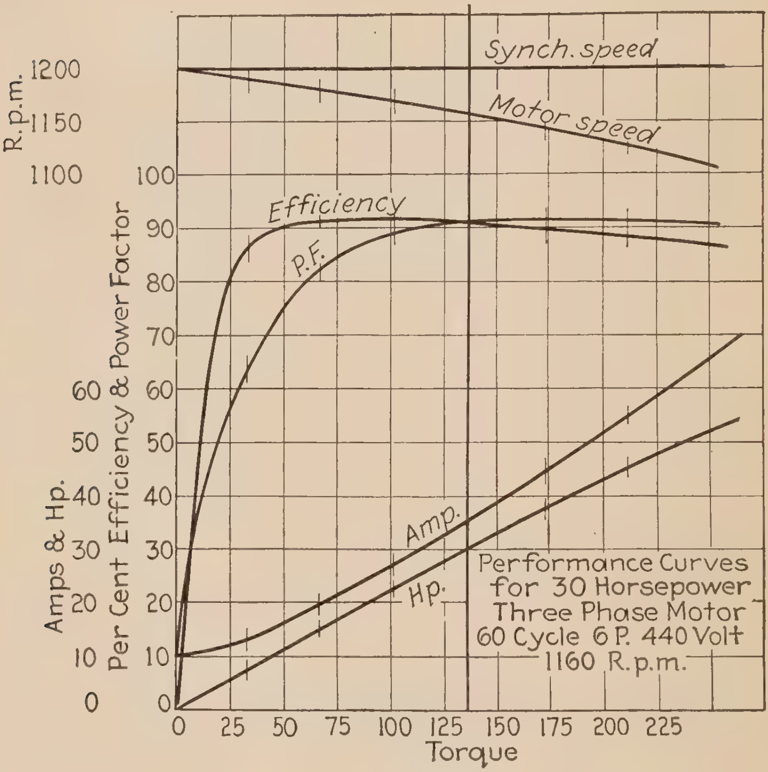

FIG. 32.—Characteristics of a 30-hp. induction motor plotted against torque.

0.85, or 85 per cent, the kilowatt input is equal to $\frac{(5 \times 0.746)}{0.85} =$ 4.4. If the full-rated-load output of the motor is 5 hp., then the half-load input will be 2.2 kw., since only the kilowatt input now

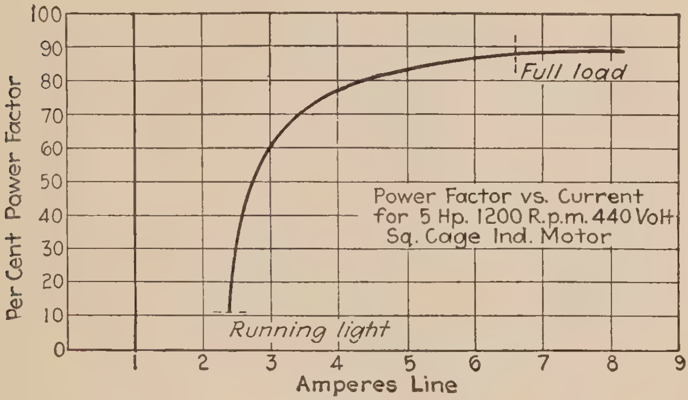

FIG. 33.—Comparison of line amperes with power factor of a 5-hp. induction motor.

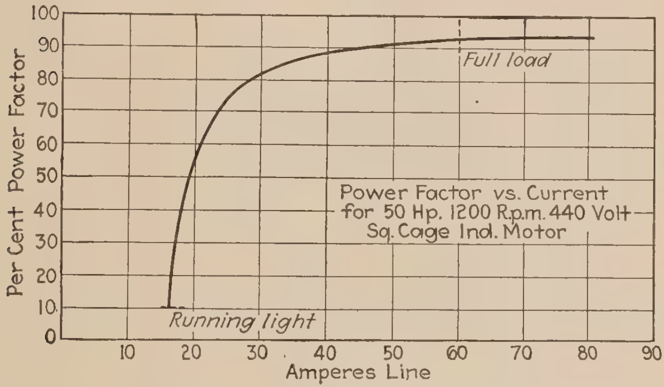

FIG. 34.—Comparison of line amperes with power factor of a 50-hp. induction motor.

is being considered. This may or may not correspond to the 50 per cent full-rated load output $\left(\frac{2.2}{2.5} = \frac{4.4}{5}\right)$, although it often does approximately.

47. The Kilowatt Input as a Function of Cot θ.—Referring to Table IX, Art. 42, kw. = cot $\theta \times$ rkw. Hence, for a given number of reactive kilowatts (lagging reactive kilovolt-amperes) the kilowatt input is directly proportional to cot θ, except in practical motors, where there is a difference which is explained further on. For the time being, however, the above relation will be assumed. This is illustrated in Fig. 35, which shows the relation of the total kilovolt-amperes to the other quantities. The relation between kw. and cot θ also is shown in Fig. 36. The line f represents the constant rkw. = 3 in this case.

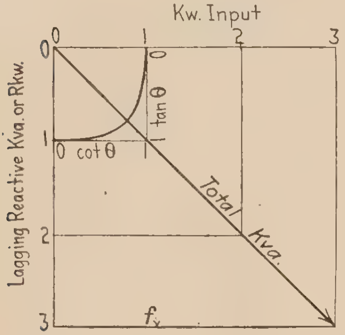

FIG. 35.—The kilowatt input as a function of cot θ. The lines representing both here are parallel. Rkw. = 3, cot $\theta = 1$. Hence, kw. = $3/1 = 3$; the kilovolt-ampere vector determining the relations. The horizontal line f indicates that rkw. is constant in this case.

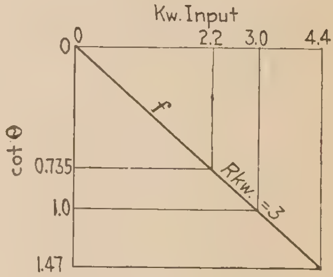

FIG. 36.—Relation between the kilowatt input and cot θ with constant rkw. In this case, the constant rkw. = 3 shows the constant relation between cot θ and kilowatt input when the reactive kilowatt line starts from the common origin 0.

While the lagging reactive component (rkw.) of the total kilovolt-amperes increases somewhat with the loads in induction motors, let it first be assumed that the reactive kilowatts remain constant as the load increases and that the motor has a full-rated-load output of 5 hp., and a full-rated-load input of 4.4 kw. Furthermore, let rkw. = 2.64 and let the efficiency be considered as borrowed from a commercial 5-hp. motor. Then the data may be determined from Table IX as in Table X.

It will be noted in the Table X that cot θ varies directly with the kilowatt input.

The data in Table XI are calculated from those in Table X, using the same borrowed efficiency curve.

The product of sin θ and kva. in the above table is equal to 2.64, the value of rkw., as assumed for the motor. Likewise, the ratio kw./cot θ, or the product tan $\theta \times$ kw., gives the constant value rkw. = 2.64.

TABLE X.—DATA FOR 5-HP. INDUCTION MOTOR

Quantity	At one-half full-rated-load kilowatt input	At full-rated-load kilowatt input
Power factor (cos θ)	0.64	0.86
Efficiency	0.84	0.85
Kilowatt input	2.2	4.4
Horsepower output	2.48	5.0
Cot θ	0.833	1.667
Tan θ	1.200	0.600
Kilovolt-amperes	3.44	5.12
Reactive-kilowatts	2.64	2.64

TABLE XI.—CALCULATED CHARACTERISTICS OF 5-HP. INDUCTION MOTOR WITH CONSTANT MAGNETIZING CURRENT

Per cent full-rated-load kilowatt input	Kilowatt input	Cot θ	Phase angle θ			Cos θ	Tan θ	Sin θ	Kilovolt-amperes
			Deg.	Min.	Decimal fraction				
10	0.44	0.167	80	32	80.53	0.164	6.00	0.986	2.68
20	0.88	0.333	71	35	71.58	0.316	3.00	0.949	2.78
30	1.43	0.500	63	26	63.43	0.447	2.00	0.894	2.95
40	1.76	0.667	56	18	56.30	0.555	1.50	0.832	3.17
50	2.20	0.833	50	12	50.20	0.640	1.20	0.768	3.44
60	2.64	1.000	45	0	45.00	0.707	1.00	0.707	3.74
70	3.08	1.17	40	31	40.52	0.760	0.856	0.650	4.05
80	3.52	1.33	36	52	36.87	0.800	0.750	0.600	4.40
90	3.96	1.50	33	41	33.68	0.832	0.667	0.555	4.76
100	4.40	1.67	30	58	30.97	0.857	0.600	0.515	5.13

Some of the data from Table XI are plotted in Fig. 37, which may be compared with Fig. 35. All of the lines connecting the origin 0 with the per cent full-rated-load kilowatt input are vectors whose lengths represent the magnitudes of the various kilovolt-amperes and whose positions indicate the angular displacements from the axis of unity power factor where $\theta = 0$, sin $\theta = 0$, and cos θ (the power factor) = 1. The cosines of these angles, that is, the lagging power factors in per cent, are given instead of the angles. The latter are given in Table XI. While the phase angle θ can be decreased below 30 deg. 58 min. by overloading the motor, thus increasing the power factor above 85.7 per cent, it is not practicable to overload the motors by more than 25 per cent for two hours or less or to cause them to carry 200 per cent load, or 100 per cent overload, but for brief intervals. Even then, a full knowledge of the particular motor

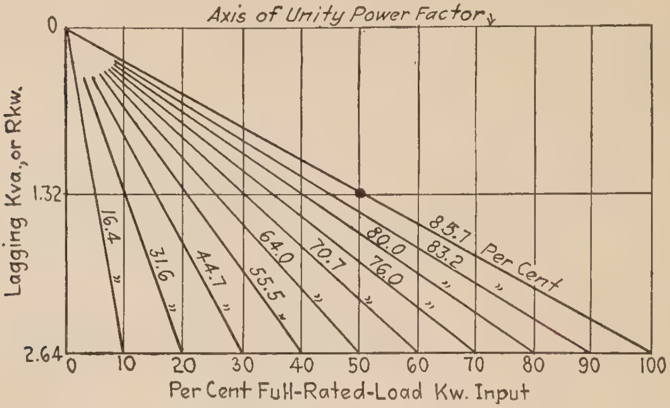

FIG. 37.—Improving the power factor of an induction motor by loading it. The power factors in per cent are marked on the kilovolt-ampere vectors. For the values of the kilovolt-ampere vectors and the corresponding phase angles, see Table XI.

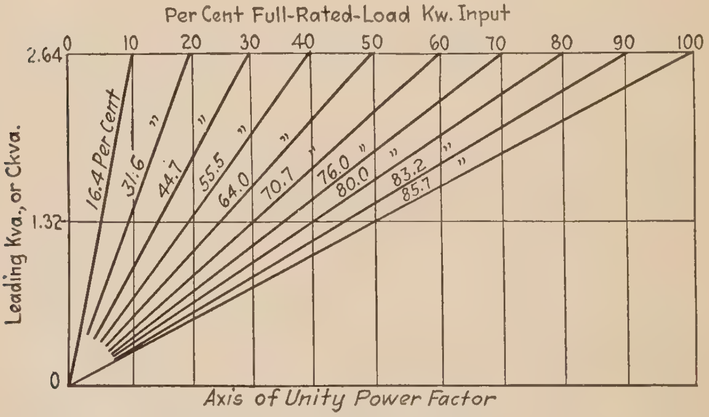

FIG. 38.—Leading kilovolt-amperes, or corrective kilovolt-amperes, required to increase the power factors in Fig. 37 to unity, for the various corresponding kilowatt inputs. The kilovolt-ampere vectors have the same corresponding magnitudes and positions as in Fig. 37, but are positive.

must be had, as to whether it is a 40 or a 50°C. motor, whether it has been repaired, and so forth. If any vector in Fig. 37 could be moved up to the axis of unity power factor by any means whatever, the power factor of the induction motor would be increased to unity, but it has never been done except by the addition of the equivalent of an exciter to supply the magnetizing current.

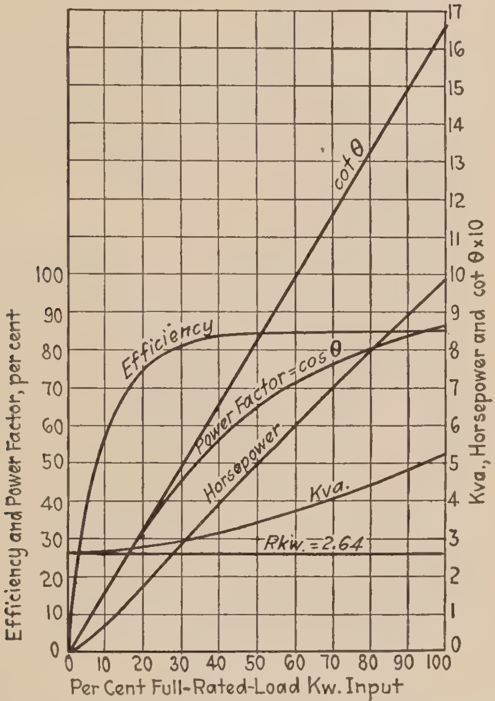

FIG. 39.—5-hp. induction-motor characteristics based on constant magnetizing current, as calculated and found, assuming the full-rated-load kilowatt input to be 4.4, and that kilowatt input/cot θ = constant rkw. = 2.64.

The kilovolt-ampere vectors in Fig. 37 show the relations between the number of reactive kilowatts and the per cent full-rated-load kilowatt input. It is to be noted that when the reactive kilowatts are constant and equal to 2.64, in this case, the vector extending from the origin 0 to 100 per cent full-rated-load kilowatt input passes through the point correlating one-half the total reactive kilowatts and 50 per cent full-rated-load kilowatt input.

By turning Fig. 37 upside down, as in Fig. 38, the vectors coordinating the corrective kilovolt-amperes (magnetizing kva.) to be supplied by power-factor-improving apparatus to make the power factor of the combination of motor and power-factor-improving apparatus unity with the various values for the kilowatt input are obtained. This will presently be taken up again in connection with power-factor correction.

Table XII gives the borrowed efficiency data from which the horsepower output is calculated, the data for the above 5-hp. motor, as calculated and found, being plotted in Fig. 39. While Table XII and Fig. 39 show about how the per cent kilowatt input and the per cent horsepower output vary with respect to each other, motors may have somewhat different ratios, as discussed further on.

TABLE XII.—FURTHER CHARACTERISTICS OF THE 5-HP. MOTOR

(*a*) Per cent full-rated-load kilowatt input	(*b*) Efficiency in per cent	(*c*) Kilowatt input	(*d*) $b \times c$	(*e*) Horse-power output	(*f*) Per cent full-load horsepower output	$\frac{a}{f}$	$\frac{f}{a}$
10	0.60	0.44	0.264	0.354	7.09	1.41	1.709
20	0.75	0.88	0.660	0.885	17.7	1.17	0.85
30	0.82	1.32	1.08	1.45	29.0	1.035	0.965
40	0.835	1.76	1.47	1.97	39.4	1.015	0.985
50	0.84	2.20	1.85	1.48	49.6	1.008	0.992
60	0.84	2.64	2.22	2.98	59.5	1.008	0.992
70	0.845	3.08	2.60	3.49	69.8	1.002	0.998
80	0.845	3.52	2.97	3.99	79.8	1.001	0.999
90	0.85	3.96	3.36	4.51	90.0	1.0	1.0
100	0.85	4.40	3.74	5.0	100.0	1.0	1.0

48. Analysis of Commercial Induction-motor Characteristics. In commercial induction motors, the line expressing the ratio between cot θ and the kilowatt input does not start from the common zero value, but cot θ has some definite value when kw. is zero; that is, a projection of the line coordinating cot θ and kw. between the limits 50 and 100 per cent full-rated-load kilowatt input cuts the vertical axis at a point above the origin 0.

The data for the 20-hp. commercial induction motor in Fig. 28, up to the full-rated-load output, are given in Fig. 40. Only the values at one-half and at full rated loads are generally given, although those for 75 and 125 per cent load factor are sometimes shown by motor manufacturers.

When the efficiencies and power factors are given for the various values of horsepower output, the kilowatt input is calculated as follows:

$$\text{kilowatt input} = \frac{\text{horsepower output} \times 0.746}{\text{efficiency}}.$$

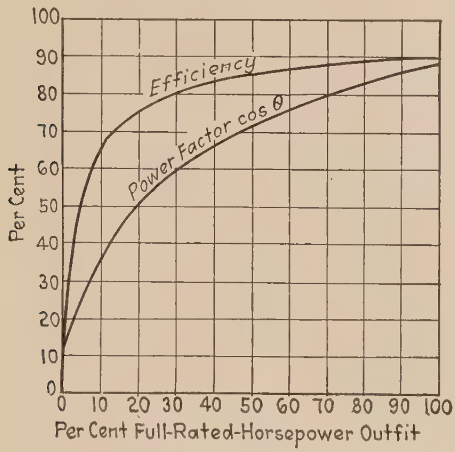

FIG. 40.—Efficiency and power factor for various outputs of 20-hp., squirrel-cage polyphase induction motor.

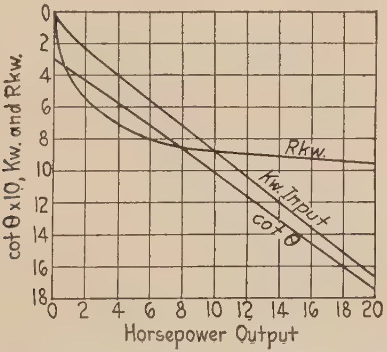

FIG. 41.—Relations between the horsepower output, kilowatt input, cot θ and rkw. for 20-hp., squirrel-cage polyphase induction motor.

This has been done in Fig. 41 and the values plotted to form a curve showing the relations between the horsepower output and the kilowatt input. It will be noted that the curves for the kilowatt input and cot θ are approximately parallel, as they should be, but that the kilowatt-input curve starts from the origin 0, while the cot θ curve has a value of about 3 when kilowatt input = 0. This is the reason why the power factor is never equal to zero in induction motors, as will be understood from Table XIII, which is compiled as follows:

Table XIII.—Fundamental Relations

Kilowatt input	Cot θ	Reactive kilowatts	Power factor, cos θ	Kilovolt-amperes
0	0.25	0	0.242	0
1	0.50	2.00	0.447	2.14
2	0.75	2.67	0.600	3.33
3	1.00	3.00	0.707	4.25

1. Various values of kilowatts are assumed.

2. Cot θ is made to start with a value of 0.25 and to increase in regular steps of 0.25 per unit of kilowatts.

3. $\text{Rkw.} = \dfrac{\text{kw.}}{\cot\theta}$.

4. The values of cos θ, the power factor, corresponding to those of cot θ, are found from a table of trigonometric functions.

5. $\text{Kva.} = \dfrac{\text{kw.}}{\cos\theta}$.

So when cot θ starts at any point above the origin 0, as it always does in induction motors, the reactive kilowatts increase with the load, and the power factor has a definite value at no load.

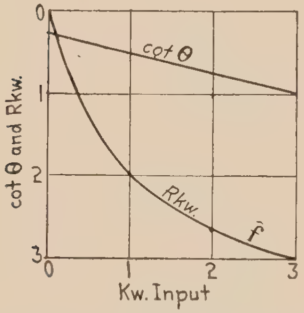

Fig. 42.—Effect of variation in relation of kilowatt input and cot θ upon the lagging reactive kilovolt-amperes (rkw.).

The data for the relations between kilowatts, cot θ, and reactive kilowatts in Table XIII are plotted in Fig. 42. The line *f* is the limiting value of reactive kilowatts as in Figs. 37 and 41, and in the following diagrams. It will be noted that the reactive kilowatts curve tends to level out in this case, as in the case of Fig. 41.

In Fig. 43, the kilowatt and reactive kilowatt curves for the per cent horsepower output of the 20-hp. polyphase induction motor are used to plot the reactive kilowatt curve corresponding to the kilowatt-input values. These two reactive kilowatt curves nearly coincide between the limits 50 and 100 per cent full rated load, either for kilowatt input or for horsepower output, and show that the number of reactive kilowatts increases with the load.

49. Overloading Induction Motors for Brief Time Intervals.—Induction motors can be loaded beyond their full rated loads providing they do not become overheated and the reduction in speed is not too great. For instance, among the various motors tested by the author was a 25-hp., 60-cycle, six-pole, 440-volt, squirrel-cage, three-phase induction motor driving a band resaw. The kilowatt input was 170 per cent full rated load during the time that kiln-dried mahogany planks were traveling to the saw at a high rate, end to end, during a portion of the time, and then the load would fall off to a lower value. The motor was shut down immediately when not needed. This motor was never unduly overloaded and its average power factor was good. What counts in such cases, within the limits of the pull-out load, are the temperature and the speed of the motor operating overloaded. An induction motor may withstand relatively great overloads for brief periods, and then run underloaded with a fair power factor for longer periods, and still not become too hot, but carry its load all day, in cases where the voltage remains normal and the variations in the speed relatively unimportant. The tendency is to run all motors underloaded with purely imaginary factors of safety in a great many cases.

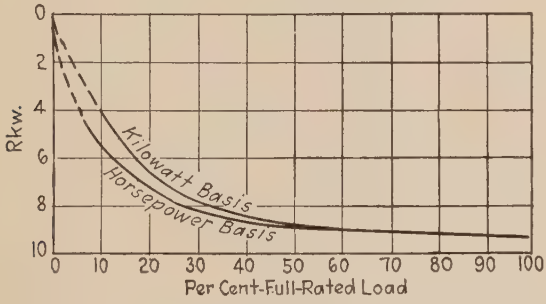

Fig. 43.—Relations between kilowatt input, horsepower output and reactive kilowatts.

The characteristics of the overloaded 20-hp., squirrel-cage, polyphase induction motor in Fig. 28, Art. 44, are the bases of the curve showing the relation between the number of reactive kilowatts and the kilowatt input from 50 to 300 per cent full-rated-load kilowatt input in Fig. 44; 300 per cent full-rated-load kilowatt input corresponds to 50 kw. and also to 50 hp. in the present case. This so happens because the efficiency is about 75 per cent with a 50-hp. load on this 20-hp. motor. Reference to Fig. 28 will show, however, that the power factor is of the order of 90 per cent. Heavy overloads cannot be maintained but for brief periods without decreasing the speed and heating the coils of the motor, and the efficiency is reduced, but the power factor tends to remain good.

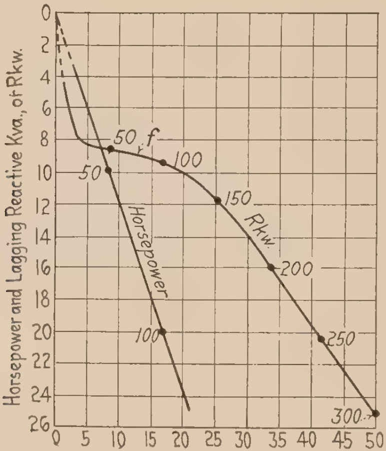

FIG. 44.—Increase in the lagging reactive kilovolt-amperes (rkw.) with overloaded 20-hp. squirrel-cage polyphase induction motor. The numbers on the curves represent the per cent full-rated-load kilowatt inputs.

CHAPTER IX

CORRECTION OF THE POWER FACTORS OF INDUCTION MOTORS

The correction of the power factor of an individual induction motor herein is used as an example, since induction motors are the principal causes of low power factor when operated underloaded. It is shown how the inherent power-factor-improving ability of the motor operates alone and in conjunction with any device or devices supplying magnetizing (leading) current. The power factor of an induction motor may be increased from the one-half to the full-rated-load kilowatt-input power factor by simply loading the motor, or else by the application of external power-factor-corrective apparatus without increasing the load above the one-half value. The amount of corrective kilovolt-ampere capacity to be applied externally to increase the power factor from any value to unity is equal, but opposite in sign, to the lagging reactive kilovolt-amperes of the motor corresponding to the lower power factor. Since the half-load and the full-load power factors are known, a simple chart is prepared which shows the general principles involved. It is to be noted that the power-factor-corrective ability of an induction motor is due to an increase in load, whereas the power-factor-corrective ability of external power-factor-corrective apparatus is independent of the load on the motor to the extent that the power factor may be increased without increasing the load on the motor.

50. The Inherent Power-factor-improving Ability of an Induction Motor.—This may be determined as described in Art. 47 in connection with Fig. 37, remembering that the power factor is $\cos \theta = \frac{\text{kw.}}{\text{kva.}}$ but it also may be determined, up to the practical limit of load, by the amount of leading or magnetizing kilovolt-amperes, or corrective kilovolt-ampere, capacity of apparatus required to increase the power factor of the motor and external corrective apparatus in combination without increasing the load on the motor. The data for a certain 25-hp., three-phase, squirrel-cage induction motor and the quantities calculated therefrom are given in Table XIV.

TABLE XIV.—DATA FOR 25-HP., SQUIRREL-CAGE, POLYPHASE INDUCTION MOTOR

Quantity	Rated load	
	One-half	Full
Kilowatt input	10.5	21.0
Power factor ($\cos \theta$)	0.84	0.91
Kva. $= \frac{\text{kw.}}{\cos \theta}$	12.5	23.1
Nearest value of θ (from $\cos \theta$)	32 deg. 52 min.	24 deg. 30 min.
Cot θ	1.55	2.19
Tan θ	0.646	0.456
Rkw. $= \tan \theta \times$ kw. $= \frac{\text{kw.}}{\cot \theta}$	6.78	9.58

The values above tabulated are only for one-half and full-rated-load kilowatt inputs. It is assumed that nothing is known regarding the motor characteristics between no load and 10.5-kw. input, because the above data are all that are usually given.

It is apparent that cot θ does not vary directly with the kilowatt input. Otherwise, rkw. $= \frac{\text{Kw.}}{\cot \theta}$ might be a constant quantity at all loads between 50 and 100 per cent full-rated-load kilowatt input instead of varying with the load. Rkw. is the lagging quadrature or reactive component of the total kilovolt-amperes. Kw. is the in-phase or active-power component of the total kilovolt-amperes. $\frac{\text{Kw.}}{\text{rkw.}}$ is the cotangent of the phase angle θ, or cot θ. $\frac{\text{Rkw.}}{\text{kw.}}$ is the tangent of the phase angle θ, or tan θ.

The above data are plotted in Fig. 45 by placing a point on the paper coordinating 10.5 kw. with rkw. = 6.78, and another point coordinating 21 kw. with rkw. = 9.58, as taken from Table XIV. Kilovolt-ampere vectors then are drawn from the common origin 0 to these respective points.

The kilovolt-ampere vector coordinating 10.5 kw. and rkw. = 6.78 shows that the total number of kilovolt-amperes is 12.5, the power factor cos θ is 0.84, or 84 per cent, and reference to Table

XIV shows that the kilovolt-ampere vector is displaced by 32 deg. 52 min. from the topmost horizontal line which is the axis of unity power factor.

The kilovolt-ampere vector coordinating 21 kw. with rkw. = 9.58 shows that the total number of kilvolt-amperes is 23.1, the power factor cos θ is 0.91, or 91 per cent, and reference to Table XIV shows that the kilovolt-ampere vector is displaced by 24 deg. 30 min. from the axis of unity power factor.

The points above referred to are, therefore, the terminals of the two kilovolt-ampere vectors respectively representing 84 and 91 per cent power factor. These two points are connected by a straight line *f* which is continued in dotted form to the point where it touches the axis (vertical) of ordinates at rkw. = 3.98, herein called the focal point for purposes of calculation. However, between the limits 50–100 per cent full-rated-load kilowatt input, that is, between 10.5 and 21 kw., the line *f* is really a part of the reactive kilowatt curve showing the relations between the kilowatt input and reactive kilowatts, as in Fig. 42, Art. 48. While the motor characteristics are unknown in this case, the curve *f* in Fig. 45 is continued to 0 in dotted form, and marked "rkw.," as in Fig. 42. A dotted kilovolt-ampere vector also is

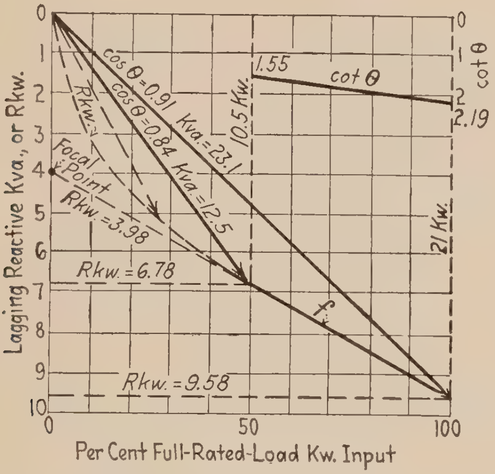

FIG. 45.—Inherent power-factor-improving characteristics of 25-hp., squirrel-cage, polyphase induction motor. The values of cos θ marked on the kilovolt-ampere vectors are the power factors. The maximum value of cos θ is 1, so cos θ = 0.84 means 84 per cent, and cos θ = 0.91 means 91 per cent, power factor.

shown to indicate that this curve is the terminus of all kilovolt-ampere vectors at whose terminals are the points coordinating the kilowatt input with the lagging reactive kilvolt-amperes, or reactive kilowatts. When this reactive kilowatts or *f* curve is inverted, it shows the number of corrective kilovolt-amperes to be supplied to correct the power factor to unity, or 100 per cent, since an equal but opposite amount of kilovolt-ampere corrective capacity must be supplied for this purpose.

The curve *f* represents the equality

$$\text{rkw.} = \frac{\text{kw.}}{\cot \theta}.$$

between the limits 50 and 100 per cent full-rated-load kilowatt input.

Cot θ is found opposite cos θ, the power factor, in a table of trigonometric functions.

The power factor is $\cos \theta = \dfrac{\text{kw.}}{\text{kva.}}$.

Kva. is measured with a voltmeter and an ammeter, or with a kilovolt-ampere meter (kva. meter).

Kw. is read directly from a kilowatt (kw.) meter.

The curve *f* is the terminus of all total kilovolt-ampere vectors when the induction motor is operating without corrective apparatus, and the corresponding values of rkw. are equal to $4.37 \times \cot \theta$ in this case.

So far as the relations between 10.5 to 21 kw. and 6.78 to 9.58 rkw. are concerned, rkw. might be equal to 3.98 at zero kilowatt input. Hence, since only the values of rkw. corresponding to the 10.5 to 21 kw. are being considered, it will be assumed that rkw. = 3.98 when kw. = 0. Under these conditions, only straight-line ratios exist, which greatly simplify the calculations.

Then the amount of reactive kilowatts developed in increasing the kilowatt input from 0 to 10.5, on this basis, is equal to 6.78 − 3.98 = 2.60 rkw., and the amount of reactive kilowatts actually developed in increasing the kilowatt input from 10.5 to 21 kw. is equal to 9.58 − 6.78 = 2.60 rkw., also. So when corrections in the power factor of this motor are to be made it may be assumed that 3.98 kva. of external corrective capacity must be supplied to correct the power factor to unity at zero load, for purposes of simply calculating the corrective kilovolt-amperes at and between the loads corresponding to 10.5 and 21 kw., respectively.

When the load is 10.5 kw. input, the actual amount of external corrective kilovolt-amperes required to increase the corresponding power factor of 84 per cent to unity is 6.78.

When the load is 21 kw. input, the actual amount of external corrective kilovolt-amperes required to increase the corresponding power factor of 91 per cent to unity is 9.58.

Hence, the rate at which the kilowatt input increases with respect to the corrective kilovolt-amperes with increases in load is equal to

$$\frac{21 - 10.5}{9.58 - 6.78} = \frac{10.5}{2.60} = 3.75.$$

That is, the kilowatt input increases 3.75 times more rapidly than the corrective kilovolt-amperes required to increase the power factor to unity. This explains why an induction motor has the inherent ability to increase its power factor when its load is increased.

On the straight-line basis previously referred to, with the kilowatt input increasing 3.75 times faster than the reactive kilowatt or the corrective kilovolt-ampere capacity (ckva.) required to neutralize it, the difference in reactive kilowatts from no load to 21 kw. is equal to 9.58 − 3.98 = 5.60.

The values of reactive kilowatts, as represented by the line *f*, and corresponding to the values of kilowatts between the limits 10.5 and 21 kw., are equal to the sum of (1) 5.60 times the ratio of the actual kilowatts to the full-rated-load kilowatt input (21 kw.) and (2) the constant number 3.98, in this case.

For example, if the kilowatt input was 14 kw., the lagging reactive kilovolt-amperes would be:

$$\begin{aligned}\text{rkw.} &= (5.60 \times (^{14}\!/_{21})) + 3.98\\ &= 3.73 + 3.98 = 7.71;\end{aligned}$$

and 7.71 kva. of corrective capacity (ckva.) would be required to increase the corresponding power factor to 100 per cent.

The data in Table XIV and Fig. 45 are taken from the given characteristics of the induction motor at one-half and full rated load. The lines *f* and cot θ are not necessarily straight, but they may be considered so between the limits 50 and 100 per cent full-rated-load kilowatt input.

The 50 per cent full-rated-load kilowatt input, 10.5 kw., corresponding to both the 84 and 91 per cent power factors in Fig. 45, are transferred to Fig. 46. In this case, the total kilovolt-amperes for 91 per cent power factor are 11.55 instead of 23.1, as in Fig. 45, because the kilowatt input is now only one-half as great and the reactive kilowatts are the same as before. For a given amount of lagging kilvolt-amperes, or reactive kilowatts, the total kilvolt-amperes are directly proportional to the kilowatt input.

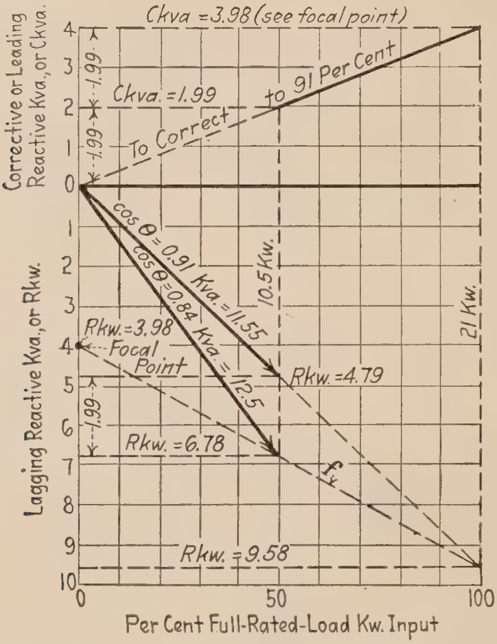

FIG. 46.—This illustration shows that 1.99 leading kva., or ckva., are required to increase the power factor from 84 to 91 per cent at half load, and that the motor has an inherent equivalent of 1.99 ckva., to increase its power factor from 84 per cent at one-half the full-rated-load kilowatt input to 91 per cent at the full-rated-load kilowatt input. This inherent equivalent ckva. is 3.98 as measured from no load to the full rated load.

There is included also in Fig. 46 the ratio of the 50 to 100 per cent full-rated-load kilowatt inputs to the corrective kilovolt-amperes, or corrective or leading kilovolt-ampere capacity, required to increase the power factor from 84 to 91 per cent when the load remains constant at 10.5 kw. input, that is, at one-half the full rated load. This magnetizing corrective kilovolt-ampere is found by multiplying the constant kilowatt input of 10.5 kw. by the *difference in the tangents of the respective phase angles.* This may be written:

$$\text{ckva.} = \text{kw.} \times \Delta \tan \theta,$$

wherein $\Delta \tan \theta$ is the difference in the tangents of the respective phase angles, Δ meaning *difference in* and $\tan \theta$ meaning *tangent of the phase angle (or angles)* θ.

The following shows the conditions in this particular case:

Kilowatt input at one-half full rated load......	10.5
Tan θ at one-half full rated load..............	0.646
Tan θ at the full rated load..................	0.456

$\Delta \tan \theta = 0.456 - 0.646 = -0.190$

$- \Delta \tan \theta = 0.190$ ($-\tan \theta$ is lagging).

The above values for kilowatts and $\tan \theta$ will be found in Table XIV together with the power factors, phase angles, and so forth.

The amount of leading kilovolt-amperes, or corrective kilovolt-amperes, required to correct the power factor at the half-load of 10.5 kw. from 84 to 91 per cent, without increasing the load on the motor, is

$$\text{ckva.} = 10.5 \times 0.190 = 1.99,$$

as determined from the above equation, which means that 1.99 kva. of power-factor-corrective apparatus must be employed to change the power factor of the induction motor from 84 to 91 per cent when the motor is running at one-half the full-rated-load kilowatt input. This reduces the external reactive kilowatts from 6.78 at 84 per cent to 4.79 at 91 per cent power factor.

The line, "To correct to 91 per cent," at the top of Fig. 46, shows that 1.99 more ckva. are required to correct the 84 per cent power factor to 91 per cent at the full rated load. Hence, the half-load power factor of 84 per cent has been increased to 91 per cent at one-half the full-rated-load kilowatt input by the addition of 1.99 ckva. and to 91 per cent at the full-rated-load kilowatt input by the addition of 1.99 more ckva., this time through the loading of the induction motor. Therefore, 3.98 ckva. are required to correct the power factor of the motor from 84 per cent at one-half the full-rated-load kilowatt input to 91 per cent at the full-rated-load kilowatt input, and 3.98 is the value of reactive kilowatts at the focal point.

Figure 47 is Fig. 46 inverted and with the line, "To correct to 91 per cent," starting at ckva. = 3.98, since the diagram is inverted and what previously was rkw. now is ckva.

A comparison of Fig. 47 with Fig. 46 shows that the line *f* in both cases represents the number of corrective kilovolt-amperes (ckva.) required to correct the power factor to 100 per cent, since the reactive kilowatts must be balanced by the corrective kilovolt-amperes in order to do so. The line, "To correct to 91 per cent," in Fig. 47 shows that 1.99 ckva. are required to increase the power factor from 84 per cent at one-half the full-rated-load kilowatt input to 91 per cent at the same load, and that it automatically gains the equivalent of 1.99 ckva. as the load increases from the one-half to the full-rated-load kilowatt input.

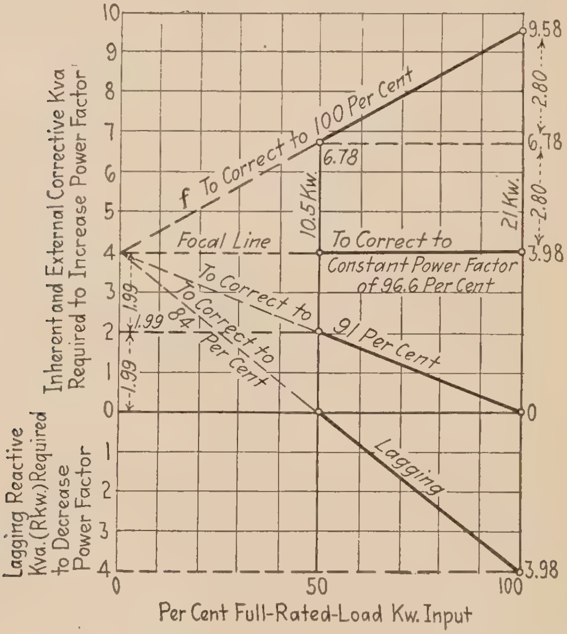

FIG. 47.—Power-factor-correction chart for 25-hp., squirrel-cage, polyphase induction motor. This motor will have a substantially constant power factor at all usual loads when 3.98 ckva. is supplied to increase its power factor to 96.6 per cent. The line marked "lagging" shows that a reactor would be required to reduce the natural power factor at full load from 91 to 84 per cent.

The line, "To correct to 84 per cent," shows that no correction is required at one-half the full-rated-load kilowatt input, and that 3.98 lagging kva., or rkw., would have to be supplied by a reactor of some sort to make the power factor 84 per cent at the full-rated-load kilowatt input.

What is the value of tan θ, the phase angle θ, and cos θ when ckva. = 3.98?

Writing the equation on page 111 as

$$\text{ckva.} = \text{kw.}\ (\tan\theta - x),$$

wherein tan θ is 0.456, corresponding to the power factor of 91 per cent, x is to be found, and rearranging,

$$\begin{aligned}\frac{\text{ckva.}}{\text{kw.}} &= \tan\theta - x,\\ x &= \tan\theta - \left(\frac{\text{ckva.}}{\text{kw.}}\right)\\ &= 0.456 - \left(\frac{3.98}{21}\right)\\ &= 0.456 - 0.190\\ &= 0.266.\end{aligned}$$

Referring to a table of trigonometric functions it is found that the angle corresponding to tan $\theta = 0.266$ is 14 deg. 54 min., and the corresponding cos θ is 0.966, or 96.6 per cent.

Hence, the power factor corresponding to ckva. = 3.98 is 96.6 per cent.

How many leading kilovolt-amperes are required to correct the 84 per cent power factor to 91 per cent at the full-rated-load kilowatt input? The answer is *none.* It is impossible to have an 84 per cent power factor with this motor running with any load over 50 per cent full-rated-load kilowatt input. However, if it is assumed for the moment that such was the case, the answer would be found as follows:

For cos $\theta = 0.84$, tan $\theta = 0.646$. For cos $\theta = 0.91$, tan $\theta = 0.456$ and

$$\begin{aligned}\text{ckva.} &= 21 \times (0.646 - 0.456)\\ &= 21 \times 0.190 = 3.98.\end{aligned}$$

How many leading kilovolt-amperes are required to correct the 91 per cent power factor to 96.6 per cent at the full-rated load kilowatt input?

For cos $\theta = 0.91$, tan $\theta = 0.456$. For cos $\theta = 0.966$, tan $\theta = 0.266$, and

$$\begin{aligned}\text{ckva.} &= 21 \times (0.456 - 0.266)\\ &= 21 \times 0.190 = 3.98.\end{aligned}$$

How many leading kilovolt-amperes are required to correct the 96.6 power factor to 100 per cent at the full-rated-load kilowatt input?

For $\cos\theta = 1$, $\tan\theta = 0$. For $\cos\theta = 0.966$, $\tan\theta = 2.66$, and

$$\text{ckva} = 21 \times 2.66 = 5.60. \quad (9.58 - 3.98 = 5.60)$$

How many leading kilovolt-amperes are required to correct the 91 per cent power factor to 100 per cent at the full-rated-load kilowatt input?

For $\cos\theta = 1$, $\tan\theta = 0$. For $\cos\theta = 0.91$, $\tan\theta = 0.456$, and

$$\text{ckva.} = 21 \times 0.456 = 9.58.$$

How many more corrective kilovolt-amperes are required to increase the power factor of 96.6 per cent to 100 per cent than to correct the 91 per cent power factor to 96.6 per cent?

$\frac{5.60}{3.98} = 1.407$. Likewise, at half-load, $\frac{2.80}{3.98} = 1.407$. Therefore, 40 per cent more corrective kilovolt-amperes are required to increase the power factor from 96.6 per cent to 100 per cent, at any load between the 50 and 100 per cent full rated loads, than are required to increase the power factor from 91 to 96.6 per cent at the same load.

The amount of corrective kilovolt-amperes required for the full rated load was used in the above examples to show the maximum amount of corrective kilovolt-amperes required. For one-half the full-rated-load kilowatt input, the corresponding corrective kilovolt-amperes are only one-half as much, varying directly with the kilowatt input between these limits. Thus, a fixed number of corrective kilovolt-amperes for a given induction motor of this type will give greater power-factor corrections at the lower loads than at the higher loads.

For instance, if 1.99-ckva. capacity is required to increase the 91 per cent power factor to 96.6 per cent at one-half load, it would increase the 91 per cent power factor only to a power factor as determined below at the full-rated-load kilowatt input.

Rearranging the equation

$$\text{ckva.} = \text{kw.} \times \Delta\tan\theta,$$

$$\Delta\tan\theta = \frac{\text{ckva.}}{\text{kw.}} = \tan\theta - x,$$

wherein x is the $\tan\theta$ to be found.

Since ckva. = 1.99 and kw. = 21,

$$\tan\theta - x = \frac{1.99}{21} = 0.0948.$$

But tan θ for 91 per cent power factor = 0.456.

Hence,
$$\begin{aligned} x &= \tan\theta - 0.0948 \\ &= 0.456 - 0.0948 \\ &= 0.355, \end{aligned}$$

which is the tangent of the angle 19 deg. 33 min. the cosine of which is 0.942.

Therefore, improving the power factor from 91 to 96.6 per cent with 1.99 ckva. at one-half the full-rated-load kilowatt input increases the power factor only from 91 to 94.2 per cent at the full-rated-load kilowatt input in this case.

Of course, 94.2 per cent is a good power factor, but the above is for illustrative purposes.

Figure 47 and the foregoing show why it is not generally profitable to increase the power factor too much above 95 per cent excepting where unity can be attained. Besides, there is danger of giving an induction motor and power-factor-corrective apparatus in combination a leading power factor which may be low when the motor is driving a very light load in its duty cycle and, therefore, does not need so much corrective capacity for a very high power factor at the full-rated-load kilowatt input. Figure 47 shows that in the case of a single induction motor supplied with constant voltage and a constant amount of corrective kilovolt-ampere capacity, it is possible to obtain a substantially constant power factor between the limits of 50 and 100 per cent full-rated-load kilowatt input, but this does not hold for very light loads. The statements in Art. 18 may be read in connection with Fig. 47.

The calculated values are marked on the various lines in the illustrations, and it is advisable to check them up by the methods described in order to understand thoroughly the simple principles involved.

To find the approximate focal point corresponding to any induction motor of this general character, simply draw a straight line connecting the terminals of the kilovolt-ampere vectors for 50 and 100 per cent full-rated-load kilowatt input, and project this line f to the axis (vertical) of ordinates or corrective kilovolt-amperes in this case.

To find the amount of external corrective kilovolt-ampere capacity necessary to increase the power factor from one value to another at a constant kilowatt input, find the tangents corre-

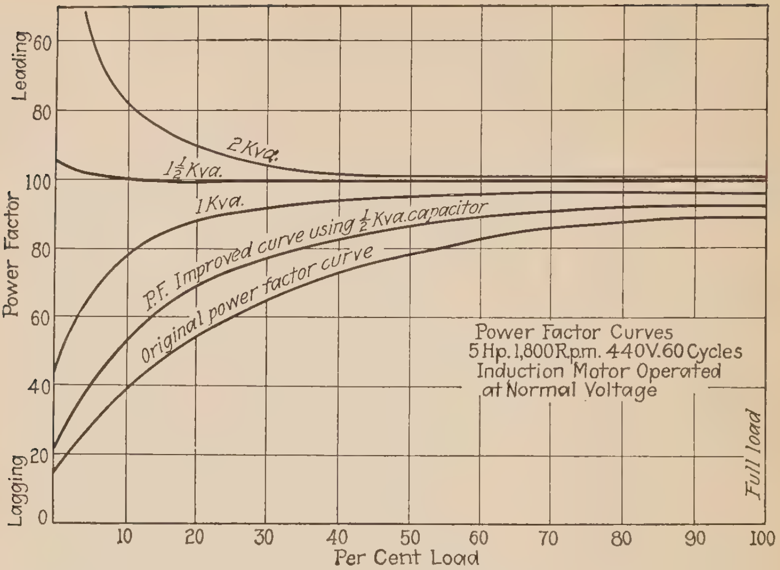

FIG. 48.—Effects of connecting various numbers of units of constant corrective kilovolt-amperes to a 5-hp. induction motor.

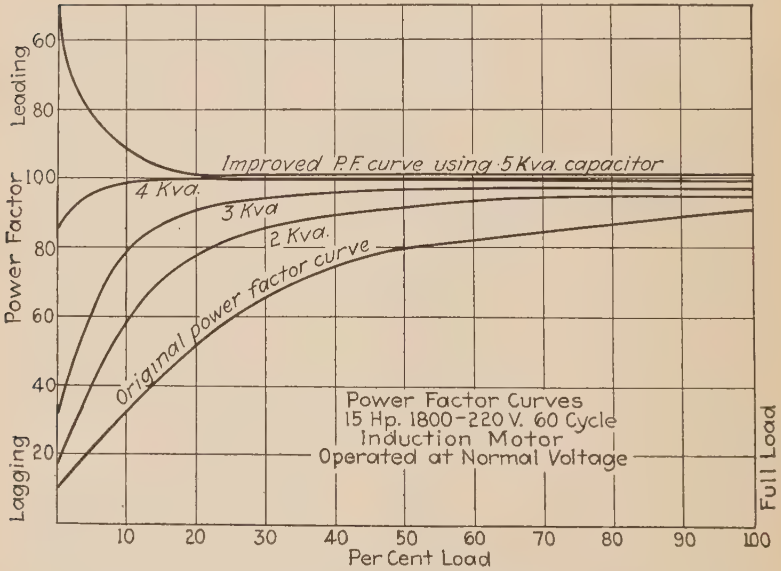

FIG. 49.—Effects of connecting various numbers of units of constant corrective kilovolt-amperes to a 15-hp. induction motor.

sponding to the respective cosines (power factors) of the two phase angles and subtract one from the other. Then multiply the difference by the constant (or average) kilowatt input. This has been explained in detail in the foregoing.

51. Effects of Constant Corrective Kva. Capacity.—Figures 48 to 50 show the effects of connecting various amounts of corrective kilovolt-ampere capacity across induction motors at various loads. It will be observed that the inherent power factor of the 15-hp. motor in Fig. 49 is about 90 per cent at the full rated load and about 80 per cent at one-half load; 5 kva. of corrective capacity makes the leading power factor about 55 per cent at no load and about 98 per cent at loads above 30 per cent, but the load is here expressed in terms of horsepower output. These three illustrations were given the author by L. W. W. Morrow, as stated in Chap. XVIII.

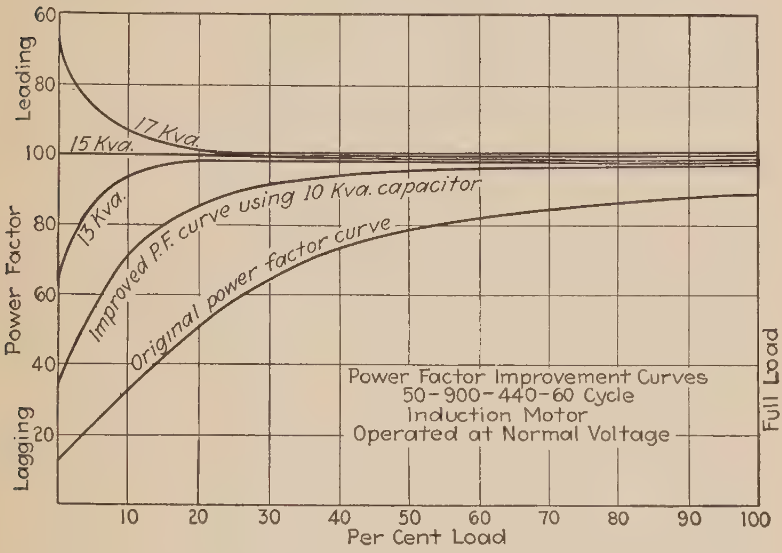

FIG. 50.—Effects of connecting various numbers of units of constant corrective kilovolt-amperes to a 50-hp. induction motor.

CHAPTER X

THE PLANT DISTRIBUTION SYSTEM

What was said in Art. 28, similarly applies to the plant distribution system, which is often the most neglected part of an industrial plant's electrical installation. In many cases, the original wiring diagrams become misplaced and lost, but often this is of small consequence since electricians are usually permitted to install such wires and cables as they deem fit, running new branches from existing mains to new motor drives, and the mains eventually become overloaded and hot. The feeders running from the meter to the switchboard or main panel also become overloaded. Some of the effects of low power factor on the distribution system are herein discussed and the modification of Kelvin's law is also mentioned, as well as the effects of variable voltages and loads on induction motors.

52. The National Electrical Code.—This is a set of rules relating to electrical installations which are intended to prevent fire hazards. But the National Electrical Code does not necessarily specify the most economical sizes of wires and cables for operating conditions. Were it not for this code, manufacturers might use smaller wires and cables than specified, that would be decided fire risks from overheating. The first costs of the wires and cables are often the primary considerations from the manufacturing executive's viewpoint.

53. Conduit.—Sometimes when larger conductors must be installed, or when changes in present distribution systems are made, it is found almost impossible to remove the conductors from the conduit. It is desirable, in many cases, to use the wire and conduit elsewhere. The explanation is very simple. The author has seen men try to pull large rubber-covered conductors through conduits too small for them. Others have told how they have installed large cables in conduits really too small for them and how many pounds of soapstone they used before succeeding. Chainfalls are used when snatch hooks fail. The material is at hand, the job must be rushed, and so extra time and labor—dollars—are expended. This is not intended to reflect on those high-class experienced electricians who are doing this work all the time. It refers particularly to those electricians who install wiring in a conduit only as occasion requires, probably not often enough. It is a wise plan to have the conduit large enough for conductors somewhat larger than those needed for the time being, because of growth and heavier loads. This should not be overdone, however, because of the increased investment.

54. How a Low Power Factor Increases the Total Current Strength and the Heating of Conductors.—For the sake of convenience in making mental calculations, let it be assumed that the current strength is 100 amp. at 100 per cent power factor in what follows, although any other number of amperes might be chosen as a basis without affecting the results which are expressed as percentages. Remembering that the power factor may be broadly defined as the ratio of the active or running current strength to the total current strength as measured with an ammeter connected in a feeder, main, branch, or tap, and that the time-rate of conversion of electric energy into heat in a conductor is directly proportional to the square of the total current strength, the following holds:

Table XV.—Effects of Low Power Factor on the Total Current Strength

Power factor, per cent	Total current strength, amperes	Per cent increase in current strength over that at unity power factor
40	250	150
50	200	100
60	167	67
70	143	43
80	125	25
90	111	11
100	100	0

TABLE XVI.—ENERGY LOST IN THE FORM OF HEAT

Power factor, per cent	Per cent lost energy in the form of heat	Per cent increase in lost energy over that at unity power factor
40	625	525
50	400	300
60	279	179
70	204	104
80	156	56
90	123	23
100	100	0

On the basis of an 80 per cent power factor, the following holds:

TABLE XVII.—EFFECTS OF LOW POWER FACTOR ON TOTAL CURRENT STRENGTH

Power factor, per cent	Total current strength, amperes	Per cent increase in current strength over that at 80 per cent power factor
40	250	125
50	200	75
60	167	42
70	143	18
80	125	0

TABLE XVIII.—ENERGY LOST IN THE FORM OF HEAT

Power factor, per cent	Per cent lost energy in the form of heat	Per cent increase in lost energy over that at 80 per cent power factor
40	625	469
50	400	244
60	279	123
70	204	48
80	156	0

In terms of the initial cost of the conductor, regardless of its length or the number of conductors in a circuit, it can be shown that the annual cost in dollars of heating an ordinary rubber-covered conductor, or a set of such conductors, having a rated current-carrying capacity of 100 amp., as specified by the National Electrical Code, would pay for at least one set of similar conductors, while the annual cost in dollars of heating a similar conductor or set of conductors when the power factor is 70 per cent (instead of 100 per cent) would purchase at least two such sets of conductors. Therefore, it is a good idea to keep the power factor within the plant as high as practicable, to avoid buying so much wire and cables without receiving them.

55. Cost of Power Losses in Electric Conductors.—This article[1] by the author was published in *Power* in substantially the same form as herein presented.

On the basis of 100 per cent conductivity copper at 68°F., it can be shown that the energy loss *per foot of single conductor* is kw.-hr. = $0.0104H\left(\frac{I}{A}\right)^2$ wherein kw.-hr. is the energy loss in kilowatt-hours, H the number of hours the current flows, I the average total current strength in amperes, and A the circular-mil cross-sectional area of the wire or cable. When the value thus obtained is multiplied by the cost in dollars per kilowatt-hour, the product is the number of dollars lost in heat per foot of wire or cable.

Recent quotations from a large local jobber on rubber-covered stranded conductors were as given in Table XIX.

TABLE XIX.—COST IN DOLLARS PER 1,000 FT.

Size in circular mils	Less than 500 ft.	More than 500 ft.
83,690	96.25	
300,000	313	294
500,000	401	376
800,000	758	711
1,000,000	930	872

It is to be noted that the heat losses are based on a conductor temperature of 68°F. Actually, the temperatures of wires indoors are considerably higher and the losses are considerably higher because of the increased resistance; so it is practicable to assume a slight difference in the cost of conductor to offset the difference in temperature in obtaining the ratio of the annual loss in dollars, due to heating the conductor, to the initial cost of conductor.

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[1] Vol. 61, p. 834, 1925.

Assuming 3,000 hours' use per year and the cost of electric energy as 2.5 cts.[1] per kilowatt-hour, the number of times that the cost of the energy used in heating the conductors per year will pay the initial cost of the same conductors can be expressed as

$$N = 1{,}000{,}000\left(\frac{I}{A}\right)^2,$$

wherein I is the average total current strength in amperes carried by the conductor and A is the cross-sectional area of the conductor in circular mils.

If the number of hours is less or the rate is greater, or *vice versa*, corrections for actual conditions are easily made. The figures given make the rule easily remembered, however, and any necessary adjustments can be made after computing on the basis given. The formula does not include conduit, labor, and so forth, but it holds for any number of wires and regardless of the number of wires.

Example 1.—The National Electrical Code allows 100 amp. as the safe current-carrying capacity of a rubber-covered wire having 83,690-circ. mil cross-sectional area of copper (size 1). This is the maximum number of amperes allowed by the code. By the foregoing formula, the number of times the money spent in heating the wire annually will pay the initial cost of the same wire, when the current strength is 100 amp., is equal to

$$N = 1{,}000{,}000\left(\frac{100}{83{,}690}\right)^2 = 1.43 \text{ times},$$

that is, 1.43 times the amount of the same wire could be purchased annually with the money that is spent in heating it, on a basis of 3,000 hours' service and energy at 2.5 cts. per kilowatt-hour. A better investment, which also would allow for growth, would be to use a cable of about 200,000 circ. mils, since then the ratio would be equal to

$$N = 1{,}000{,}000\left(\frac{100}{200{,}000}\right)^2 = 0.25,$$

that is, four years would be required to spend enough money in heating the cable to buy a new one. An idea of what the cost of money losses is may be had by referring to Table XIX.

Example 2.—The National Electrical Code permits 200 amp. as the safe current-carrying capacity for 200,000-circ. mil rubber-covered cable. Hence,

$$N = 1{,}000{,}000\left(\frac{200}{200{,}000}\right)^2 = 1,$$

that is, a new cable could be purchased every year with the money that is spent in heating it during the same period. It is to be understood, of course, that prices vary, but the object of this article is to show how much money may be unnecessarily spent in heating wires and cables. Frequently, a conductor is carrying more current than is actually known. When conductors are not carrying the currents specified as the limits for those conductors, the condition is often favorable toward saving money.

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[1] This is usually taken as 3 cts.

Referring to example 2, let the power factor be 55 per cent on a constant-voltage balanced system. Then, if the power factor was increased to 70 per cent, the current strength would be reduced to $200(55/70) =$ 157 amp., and

$$N = 1{,}000{,}000\left(\frac{157}{200{,}000}\right) = 0.62,$$

which means that the money spent in heating the cable when the power factor is 70 per cent is but $0.62 \times 100 = 62$ per cent of that when the power factor is 55 per cent.

Increasing the power factor from 60 to 75 per cent would reduce the number of amperes from 200 to $200 \times (60/75) = 160$, and

$$N = 1{,}000{,}000\left(\frac{160}{200{,}000}\right)^2 = 0.64,$$

meaning that only 64 per cent as much money need be spent in heating the cable when the power factor is 75 per cent as when it is 60 per cent.

These savings have nothing to do with the power-factor penalty or bonus, and they cannot be realized with any form of power-factor-corrective apparatus located at the plant meter.

The savings in terms of a 200,000-circ. mil cable due to improving the power factor from 40 to 80 per cent are as follows:

Amperes at 40 per cent power factor = 200, and a new cable could be bought each year with the money annually spent in heating it. Amperes at 80 per cent power factor = 100, and

$$N = 1{,}000{,}000\left(\frac{100}{200{,}000}\right)^2 = 0.25,$$

which, in plain English, means that when the cable is carrying the specified current with a 40 per cent power factor, it costs four times as much to operate it, on the initial cost of cable basis, as when the power factor is 80 per cent. Looking at the matter from a somewhat different angle, a conductor which would not carry the current when the power factor was 40 per cent would carry the necessary current when the power factor was 80 per cent.

Referring to example 1, if $N = 1.43$ with a 100 per cent power factor, if the power factor dropped to 70 per cent the current would increase to $100(100/70) = 1.43$ amp., and

$$N = 1{,}000{,}000\left(\frac{143}{83{,}690}\right)^2 = 2.92.$$

It is believed that the greater part of the power-factor wastes will be found in the same places where the low power factors originate.

The following[1] is of interest:

It is assumed that the sole effect of the increased investment (aside from the corresponding increase in fixed charges) is the reduction in fuel consumption. In short, it is assumed that the increased expenditure will necessitate no change in labor cost, reliability, life of equipment, etc.

With these assumptions, which frequently fit the practical case, the formula is:

$$I = 4.38 \frac{WFP}{f}$$

where I = maximum additional investment, in dollars per installed kilowatt, justified by the anticipated coal saving, W pounds per kilowatt-hour.

F = fuel cost (including cost of fuel handling, firing, and ash handling), dollars per ton.

f = fixed charges (interest, depreciation, taxes, etc.) per kilowatt of installed capacity on additional investment, per cent.

P = yearly plant factor, per cent.

To break even, the additional investment I per installed kilowatt must yield at least the fixed charges $\frac{fI}{100}$ per year. Fuel cost F dollars per ton, or $\frac{F}{2{,}000}$ dollars per pound. The saving in fuel cost is then $\frac{WF}{2{,}000}$ dollars per kilowatt-hour.

The kilowatt-hour output per year per installed kilowatt will be $24 \times 365 \times \left(\frac{P}{100}\right) = 87.6P$, giving corresponding yearly saving in fuel cost per intalled kilowatt of $87.6P \times \left(\frac{WF}{2{,}000}\right) = 0.0438\ WFP$ dollars.

To break even, this must equal the fixed charges. Hence,

$$fI = 0.0438\ WFP, \quad \text{or} \quad I = 4.38 \frac{WFP}{f}.$$

For example, with a plant factor of 40 per cent, a fuel cost of $6 per ton (including firing, handling, etc.) and fixed charges of 15 per cent, the maximum increase in investment justified by a saving of 0.1 lb. of coal per kilowatt-hour would be:

$$I = 4.38 \times 0.1 \times 6 \times {}^{40}/_{15} = \$7 \textit{ per kilowatt.}$$

56. Kelvin's Law.—This relates to the economical selection of conductors, deduced by Sir William Thomson (Lord Kelvin) in 1881. It has been modified by Gisbert Kapp and is now stated as follows: The most economical cross-sectional area of a conductor is that for which the annual cost of energy wasted is equal to the investment of that part of the capital outlay which can be considered proportional to the weight of copper used. From this law it can be shown that

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[1] "What is Increased Efficiency Worth?" *Power*, vol. 62, p. 677, 1925.

$$\text{circular mils} = 55{,}867 \times I \times \sqrt{\frac{C_e}{(C_c \times A)}}$$

wherein circular mils is the cross-sectional area of the most economical conductor in circular mils, I the mean annual current, C_e the cost of energy per kilowatt-hour in dollars, C_c the cost of copper in dollars per pound installed, and A the annual charge in per cent on the cost of the conductor.

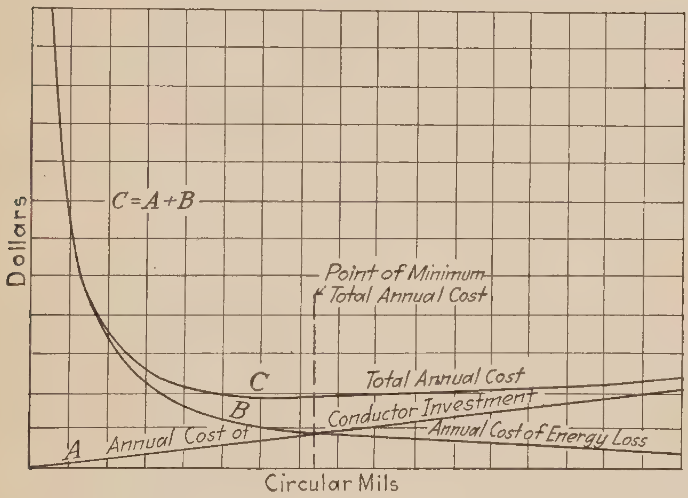

FIG. 51.—Principle of Kelvin's law. While the heat losses vary directly as the square of the total current strength, the monetary losses vary directly with the total current strength. The case of least operating cost is when the annual cost of conductor investment is equal to the annual cost of energy loss.

The best way to approach the subject is to assume that the conduit is up and that all of the labor has been performed. Then a few trial calculations can be made to ascertain the most economical size of conductor with the corresponding size of conduit. These two costs must be juggled to fit the case. Figure 51 shows the principle. It will be noted that under the conditions of Kelvin's law the cross-section of conductor varies directly with the number of amperes.

The weight of copper may be determined (approximate for stranded conductor) from the circular-mil cross-section as follows:

$$\text{Pounds of copper per foot} = 2.92 \times \frac{\text{circular mils}}{1{,}000{,}000}.$$

Thus, for a 200,000-circ. mil cable, regardless of the kind of insulation, pounds of copper per foot $= 2.92 \times \frac{200{,}000}{1{,}000{,}000}$

$$= 2.92 \times 0.2 = 0.584 \quad \text{(approximately)}$$

If there are three such conductors and each is 100 ft. long, the weight of copper in the cable is equal to 300 × 0.584 = 175 lb.

57. Voltage Drops in Plant Distribution Systems.—Rubber cannot endure a temperature greater than 150°F. without aging; so this limiting temperature insures the maximum life of the rubber. The current that will cause the ordinary insulation on a conductor to smoke is about three times the safe value.

A voltage drop of 3 per cent in motor circuits is very good practice, but much greater drops are often found. A voltage drop greater than 3 per cent, however, will affect lamps connected through transformers on the same circuits. Voltage drop in conductors is closely associated with conductor economy since the voltage drop is directly proportional to the number of amperes.

Table XX[1] shows currents causing a drop of 1 volt in circuits of different lengths.

All of the foregoing refers to the way things should be, but not to the way they often are found. New installations may have relatively small resistance drops in voltage, but installations that were new 10 years ago are old today. They may have been properly designed and installed 10 years ago, but today a very great many of them are not like what they used to be. Low and variable voltages are most often found in old installations where the original feeders and mains, and often branches, still remain although additional motors have been added from time to time until some of the mains and branches are hot and the feeders overheated. This is not good practice and should not be permitted by the insurance inspectors, but many such cases exist just the same. With one hand, the author has plucked long pieces of insulation from feeders. Electricians know that such conditions sometimes exist because they note the sizes of the wires and can feel how warm or hot they are. Things are not always just what they are supposed to be and such practical details are not often found in textbooks.

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[1] "Standard Handbook for Electrical Engineers," Sec. 13–72, 5th ed., New York, 1922.

TABLE XX.—CURRENTS CAUSING A DROP OF 1 VOLT IN CIRCUITS OF DIFFERENT LENGTHS AND OF DIFFERENT SIZES OF WIRE

Size A.W.G.	Total length (*single distance*) of circuit in feet (The total length of wire is twice the single distance)								
	20 ft.	30 ft.	40 ft.	50 ft.	60 ft.	70 ft.	80 ft.	90 ft.	100 ft.
14	9.3	6.2	4.6	3.7	3.1	2.5	2.3	2.0	1.8
12	14.8	9.9	7.4	5.9	4.9	4.2	3.7	3.3	2.9
10	23.6	15.7	11.8	9.4	7.8	6.7	5.9	5.2	4.7
8	33.0	25 0	18.7	15.0	12.5	10.7	9.3	8.3	7.5
6	46.0	39.7	29 7	23.8	20.0	16.9	14.8	13.2	11.8
5	54.0	50 0	37.6	30.0	25.0	21.2	18.7	16.1	15.0
4	65.0	63.2	47.4	37.8	31.6	27.0	23.6	21.0	18.8
3	76.0	76.0	59.8	47.7	39.6	34.0	29.8	26.2	23.8
2	90.0	90.0	75.0	60.0	50.0	42.8	37.5	33.0	30.0
1	107.0	107.0	93.5	75.0	68.0	53.5	46.7	41.5	37.4
0	127.0	127.0	119.8	95.6	79.0	68.0	59.5	53.0	47.6
00	150.0	150.0	150.0	120.0	100.0	86.0	75.0	66.5	60.0
000	177.0	177.0	177.0	152.0	127.0	108.0	95.0	84.0	76.0
0,000	210.0	210.0	210.0	192.0	160.0	136.6	120.0	107.0	96.0
200,000 c.m.	200.0	200.0	200.0	181.9	151.5	129.9	113.6	101.0	90.9
300,000 c.m.	270.0	270.0	270.0	270.0	227.2	194.7	170.4	151.5	136.2
400,000 c.m.	330.0	330.0	330.0	330.0	303.0	259.7	227.2	202.0	181.8
500,000 c.m.	390.0	390.0	390.0	390.0	378.8	324.7	284.1	252.5	227.2
600,000 c.m.	450.0	450.0	450.0	450.0	450.0	389.5	340.8	303.0	272.7
700,000 c.m.	500.0	500.0	500.0	500.0	500.0	461.0	397.7	353.5	318.1
800,000 c.m.	550.0	550.0	550.0	550.0	550.0	519.5	454.4	404.0	363.6
900,000 c.m.	600.0	600.0	600.0	600.0	600.0	584.4	511.3	454.5	409.0
1,000,000 c.m.	650.0	650.0	650.0	650.0	650.0	650.0	568.7	505.0	454.5

58. Effects of Voltage Drops on Induction Motors.—Induction motors are very sensitive to variations in the impressed voltage. The torque or turning ability of induction motors varies over a wide range as the square of the voltage at their terminals. This can be proved by trying to run an induction motor on various taps of the compensator, if continued only for brief periods so as not to overheat the coils of the compensator or the motor. Therefore, the reduction in voltage at the motor terminals has a pronounced effect upon the ability of the motor to carry its load, and may be the cause of its stopping if the voltage is so low as to bring the pull-out torque down to the torque required to run the load. A decrease in impressed voltage from 100 to 80, or any 20 per cent drop, would cause the maximum horsepower output and the maximum starting torque to decrease from 100 per cent to 64 per cent and roughly would cause a proportional increase in the heating of the wires in the motor for a given load.

Table XXI[1] shows various relations on the above basis.

TABLE XXI.—EFFECTS OF CHANGES IN VOLTAGE AT TERMINALS OF THREE-PHASE INDUCTION MOTORS

Voltage at motor in per cent of line voltage	Line starting current in per cent of full-load current	Motor starting current in per cent of full-load current	Starting torque of motor in per cent of its full-load running torque
40	112	280	32
60	250	420	72
80	450	560	128
100	700	700	200

Table XXI shows why compensators and other starting devices are used with induction motors of 10-hp. and greater ratings.

As the voltage at the motor terminals is reduced, the torque is reduced as in Table XXII.

TABLE XXII.—EFFECT OF VOLTAGE ON TORQUE

Per cent rated voltage	Per cent full-load running torque
80	64
85	72
90	81
95	90
100	100

The slip of an induction motor is a measure of the heat loss in the motor. The induction motor is analogous to a mechanical-friction coupling wherein the friction torque between the two faces is proportional to the slip. The slip varies inversely as the square of the terminal voltage. An induction motor running at full rated load and with the rated impressed voltage at its terminals will have a slip of about 5 per cent, but at the pull-out load, corresponding to about two and a half times the full rated load, where the motor stops running, the slip may be nearly 15 per cent just before the motor pulls out. The effect of voltage upon slip is shown in Table XXIII.

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[1] "Standard Handbook for Electrical Engineers," Sec. 7–220, 5th ed., New York, 1922.

TABLE XXIII.—EFFECT OF VOLTAGE ON SLIP

Per cent full rated voltage	Per cent increase in slip	Slip based on 5 per cent at full rated load of motor	Per cent difference in speed
80	56	7.8	2.8
85	38	6.9	1.9
90	23	6.2	1.2
95	11	5.6	0.55
100	0	5.0	0

While the per cent difference in speed due to variations in voltage may not be so very pronounced when the load is constant, the combination of variations in voltage and variations in load does make the per cent difference in speed quite noticeable in old installations, particularly when the voltage is low when the load is a maximum. That is why a combination of correct drives and increased power factor shows increases in production after changes in motors and the installation of power-factor-corrective apparatus have been made. Naturally, this may not amount to so much in some plants as in others.

All of the above assumes a constant voltage at the meter. When the utility's line voltage also varies, the conditions become worse. Any consideration of voltage drops at the motor terminals should include too small wiring in old plants, as well as low power factors, and long feeders too small for the current demanded by the load.

During a conversation with O. A. Kenyon, the subject was discussed and the author asked him to set down in writing his experiences with low voltage. The following letter is the result:

> In accordance with our conversation of the other day, here is a story of power factor taken from my own experience.
>
> Several years ago I installed an extensive welding plant in the Bossert Corporation, Utica, N. Y. This plant consisted of several groups of series arcs, the generators being driven by 30- and 60-hp. squirrel-cage induction motors. The 30-hp. motors furnished power for six arcs and the 60-hp. motors for twelve arcs. The welding generator was a special machine designed to give constant current with voltage automatically varied to maintain constant current.
>
> At times we had trouble when operating full capacity due to excessive drop in speed of the induction motors. We found that this drop was

due to an excessive voltage drop, and the practical effect was that we could operate only five and four arcs off of a six-arc machine when these voltage conditions obtained.

I complained about the voltage to the plant electrician, the Bossert Corporation complained to the power company, and the power company pleaded power factor. The Bossert Corporation did not understand power factor and could not be persuaded that it was not the fault of the power company that the voltage was so low. Finally, rather than spend any money on power-factor correction, they rewound all the motors in the plant for 440 volts and changed the transformers, leaving the wiring as it was. In less than a year they were having the same trouble again, and the power company took the same stand. In fact, this trouble was so serious that induction motors were sometimes unable to carry their loads and came to a standstill in the midst of an overload. This time, however, after calling in the General Electric Company to take up the matter with the power company, they decided on power-factor correction and installed a synchronous condenser. Since that time they have had no trouble from low voltage and overloading of motors.

Another instance which I recall was an experience at the plant of the Hoover Company, makers of vacuum cleaners. One day due to an accident on the line, the voltage at the plant was very low. I came into the plant with the superintendent and found that many of the departments were having trouble and others were shut down entirely due to inability of the motors to carry their load. We immediately inquired whether or not the air compressor which was run by a synchronous motor was shut down, and the engineer in the power house replied, "Yes, we need all the power we can get and we can do without the air compressor." This, of course, was the worst thing he could have done; so we immediately started up the air compressor and the plant began operation throughout in spite of the low voltage, due entirely to the corrective effect of the synchronous motor.

Very truly yours,
Otis Allen Kenyon.

CHAPTER XI

SYNCHRONOUS MACHINERY IN POWER-FACTOR CORRECTION

Synchronous condensers are used in substations and other locations for maintaining power factors and voltage regulation of transmission and distribution systems. Sometimes synchronous condensers are located on the property of the consumer. In mills requiring large constant-speed motors, synchronous motors may be used to good advantage for driving certain machinery at a high power factor.

59. Synchronous Motors in the Cement Industry.—Figure 52 shows a 500-hp. synchronous motor driving a compeb mill. The device at the right of the synchronous motor is a magnetic clutch. In cases where great starting torques are required, the motors can be started without load and brought up to speed, after which the load can be applied gradually by closing the direct-current circuit in which the coil of the magnetic clutch is connected. In certain cases, as a compeb mill in the cement industry,[1] the starting torque may be 150 per cent of the full motor torque on account of the high static friction.

The clutch generally is designed to transmit the maximum horsepower which the motor can develop, and may be connected directly across the line, allowing the mill to come up to speed as quickly as the clutch permits. Direct current is required for excitation at 110 or 120 volts. The exciter generator for the synchronous motor may be used, in many cases, as the source of energy for the clutch. The torque of the clutch increases as time elapses after the full-line voltage is applied, requiring 6 sec. in some cases, owing to the great electromagnetic inertia of the magnetic clutch. During this period the motor is accelerating and the clutch is gradually increasing the load on the motor.

The Westinghouse Electric & Mfg. Co. has developed a new high-torque synchronous motor, also known as a unity-power-factor clutch-type motor, consisting of a standard synchronous motor and a magnetically-controlled friction clutch combined to form a compact unit within the common casing. As compared with a wound-rotor induction motor it has the advantages of lower starting current and better operating power factor and efficiency. A number of motors of this type have been in successful operation in cement plants for nearly a year, while others are driving ball mills in a copper ore plant, and also in a paper mill for driving beaters, jordans, and so forth, through line shaft-

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[1] COSTELLO, W. H., "Magnetic Clutches in the Cement Industry," *Trans.* A. I. E. E., p. 361, 1922.

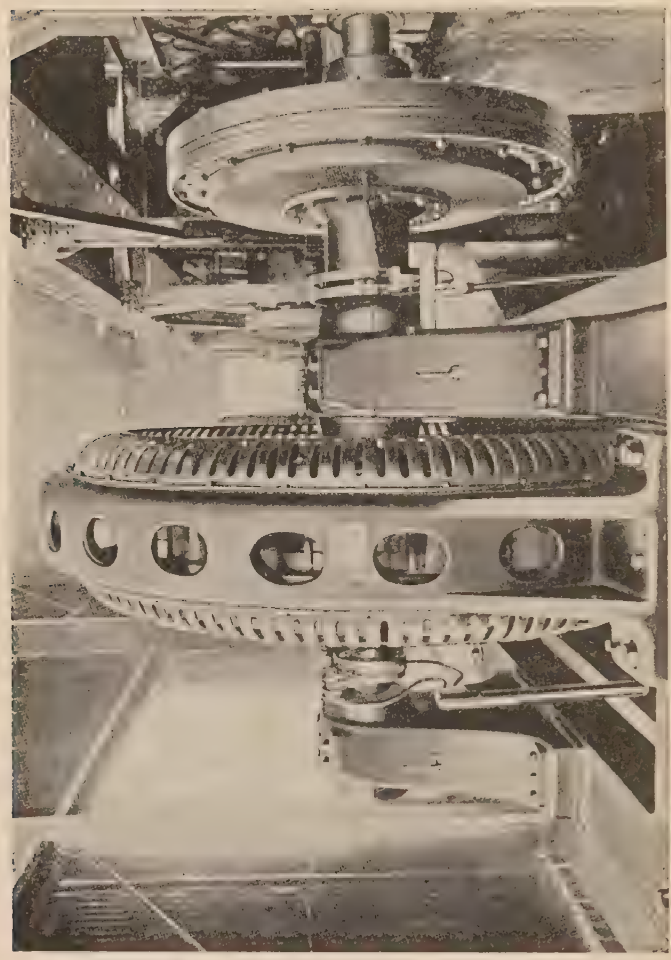

FIG. 52. 500-hp. synchronous motor driving a compeb mill through the intermediary of a Cutler-Hammer magnetic clutch. Merely closing the control switch causes the clutch to engage and connect the load to the motor. The time required for the current to build up in the magnetic clutch gives the motor time to reach synchronous speed as the clutch gradually takes hold. The exciter is located elsewhere.

ing. The motor also will be applied to centrifugal pumps, compressors, cement grinders, and ore crushers, according to Q. Graham in the January, 1926, issue of *The Electric Journal.* The rotor is not keyed to the shaft, as in ordinary synchronous motors, but is carried on roller or ball bearings mounted on the spider hub, and which permits the rotor to revolve freely when the shaft is stationary. The field member of the magnetic clutch is bolted to the side of the spider. The armature member of the clutch, which is the driven half, is mounted on a hub securely keyed to the shaft. The load to be driven is coupled or belted to the shaft in the usual way. This permits the connected load to be shut down without stopping the motor, which then may run as a synchronous condenser for power-factor correction.

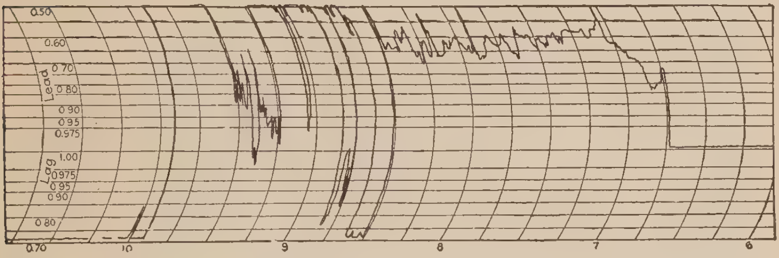

FIG. 53.—Extreme variations in power factor due to unattended synchronous condenser.

The General Electric Company produced a unity-power-factor motor some years ago wherein the stator revolves with the rotor in starting and then is brought to rest by means of a brake.

60. Synchronous Condensers.—In an article[1] by L. W. W. Morrow,[2] from which the data in the following articles are also obtained, it is stated that a 1,500-kva., 900-r. p. m., 440-volt synchronous condenser in the plant of the Witherow Steel Company was employed to correct the power factor. There were about 175 induction motors in operation. All of these, except two, were of the squirrel-cage type. A synchronous motor rated at 570 amp., 440 volts, three-phase, 60 cycles was the driving member of a motor-generator set to supply direct current to the cranes. The demand of the plant was about 1,000 kw. and the power factor before correction was about 70 per cent.

[1] "Power Factor in Practice," *Elec. World,* vol. 86, p. 213, 1925.

[2] Manager Editor of the *Electrical World.*

The use of the motor generator and synchronous condenser increased the plant power factor to about 90 per cent.

Figure 53 shows an extreme variation in the power factor due to the unattended synchronous condenser. Owing to the heavy and intermittent loads and the changing production requirements, the power factor and voltage regulation vary unless the synchronous equipment is grouped together and an attendant is always present, or else automatic devices are used to control the machines.

61. Synchronous Apparatus on the Duquesne Light Company's System.—In the article above referred to, M. E. Skinner, commercial manager, made the following statements:

> We believe power-factor correction is good business for both ourselves and our customers. We have instituted corrective measures at our own expense by locating synchronous condensers at appropriately located substations and have a number of 3,750-kva. and 7,500-kva. units in operation. This plan has been followed since 1916 and at present there are 45,000 corrective kva. of this character installed. About two years ago, it was decided to institute a power-factor clause in our wholesale rate schedules which would be available to customers on an optional basis. This clause provides a penalty in a bill if the power factor is below 75 per cent and a bonus between this value and unity. The power factor of 75 per cent was the average power factor of the power customers, and it was thought the power revenue would not be affected, since it was estimated the penalties and bonuses would equal each other. In its practical application this clause was instituted by installing reactive kilovolt-ampere-hour and kilowatt-hour meters, and then using the ratio of these readings to determine the amount of discount or penalty to apply to the customer's bill. The maximum discount amounted to 8.8 per cent of the power bill if the customer made correction to unity power factor.
>
> A clause based on the continuous record of meters was chosen, because a very large percentage of our load is taken by large users where monthly bills run into large figures and where changing conditions render any method based upon periodic tests open to question. Meters are ratcheted[1] for lagging power factor only, thus preventing abuse by carrying heavy leading power factor with light loads.
>
> This clause is being put into effect gradually, because it was felt desirable to find out by field experiences its full possibility for securing correction. After trials over a period of time, we found that the clause would secure power-factor correction if applied to large-power cus-

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[1] So that they cannot run backwards.—EDITOR.

TABLE XXIV.—MONTHLY TABULATION OF THE RESULTS OF POWER-FACTOR CORRECTION FOR SEVERAL DUQUESNE LIGHT COMPANY CUSTOMERS

Customer	February		March		April		May		June	
	Kilo-watt-hours	Power factor	Kilo-watt-hours	Power factor	Kilo-watt-hours	Power factor	Kilo-watt-hours	Power factor	Kilo-watt-hours	Power factor
American Steel Foundries	79,250	99.8	85,100	99.6	95,950	99.2	100,350	99.5	96,750	99.7
Crucible Steel Co.	924,500	85.1	940,000	83.9	870,000	83.8	643,000	83.2	258,000	77.2
Dilworth Porter Co.	184,000	95.3	169,600	95.5	172,800	94.4	160,000	94.4	140,800	94.9
Flannery Bolt Co.	42,600	70.9	66,300	84.9	81,050	89.9	62,300	86.2	36,350	77.0
National Tube Co. No. 1	454,000	100.0	503,000	100.0	490,000	100.0	470,000	100.0	420,000	100.0
National Tube Co. No. 2	....	.....	56,500	100.0	71,650	100.0	88,750	100.0	97,800	100.0
Pittsburgh Screw & Bolt Co.	260,500	83.8	273,800	84.0	251,450	86.4	212,200	90.3	194,500	93.9
Pittsburgh Seamless Tube Co.	508,500	94.0	445,500	94.8	510,500	94.8	624,500	94.2	542,000	93.7
Riter-Conley Co.	333,200	99.3	330,600	96.5	331,200	97.1	258,600	95.4	262,800	97.2
Superior Steel Corp.	984,000	98.1	916,000	99.6	752,000	100.0	596,000	99.9	480,000	99.5
Standard Gauge Steel Co.	56,700	99.1	115,250	99.7	109,700	99.2	79,750	99.9	81,650	99.1
Union Electric Steel Co.	237,000	84.5	298,300	88.7	239,150	87.9	239,150	90.5	225,650	90.2
Vanadium Corporation of America No. 1	2,608,000	94.6	2,829,500	94.6	2,602,500	95.2	2,887,000	95.4	2,623,000	95.2
Vanadium Corporation of America No. 2	461,500	99.7	511,000	99.6	501,500	99.7	508,000	99.8	496,500	99.8
Columbia Steel Shafting Co.	30,350	75.1	81,600	75.1	93,600	78.2	97,650	81.2	74,600	91.0
Witherow Steel Co.	....	.....	....	.....	67,650	88.5	142,000	92.8	84,700	97.0
National Tube No. 3	....	.....	....	.....	276,500	60.3	610,000	63.2	640,500	58.5
Universal Steel Co.	181,000	86.9	940,500	86.6	486,000	85.4	476,500	85.6	327,000	85.9
Average power factor	....	91.1	....	92.7	....	91.1	....	91.75	....	91.66

TABLE XXIV.—(*Continued*)

Customer	July		August		September		October		November	
	Kilowatt-hours	Power factor	Kilowatt-hours	Power factor	Kilowatt-hours	Power factor	Kilowatt-hours	Power factor	Kilowatt-hours	Power factor
American Steel Foundries	101,350	99.8	91,350	99.9	86,750	99.8	100,300	99.9	107,150	99.1
Crucible Steel Co.	187,000	79.8	80,000	64.5	504,000	77.0	214,000	79.7	800,000	84.0
Dilworth Porter Co.	116,800	92.7	88,000	97.6	84,000	97.2	80,800	98.0	118,400	94.2
Flannery Bolt Co.	32,300	74.3	50,650	90.8	51,600	90.2	59,800	93.2	54,850	94.9
National Tube Co. No. 1	722,000	100.0	378,000	100.0	252,000	100.0	174,000	100.0	258,000	100.0
National Tube Co. No. 2	74,100	100.0	114,900	100.0	78,950	100.0	49,600	100.0	16,850	100.0
Pittsburgh Screw & Bolt Co.	145,200	94.1	130,700	88.1	209,250	92.1	208,800	90.0	195,200	90.8
Pittsburgh Seamless Tube Co.	561,000	95.3	690,500	93.1	566,000	94.6	530,500	93.0	470,500	94.3
Riter-Conely Co.	223,800	97.5	182,400	99.0	211,800	99.6	202,200	99.8	199,800	99.8
Superior Steel Corp.	240,000	99.6	544,000	99.4	664,000	100.0	576,000	99.9	720,000	99.4
Standard Gauge Steel Co.	67,050	98.9	67,650	99.0	77,350	99.2	92,900	99.4	80,750	97.6
Union Electric Steel Co.	254,650	88.7	230,000	87.4	118,050	86.9	167,550	87.9	175,000	90.0
Vanadium Corporation of America No. 1	2,871,500	95.4	2,930,500	95.4	3,030,000	95.5	2,947,000	94.4	2,776,000	93.2
Vanadium Corporation of America No. 2	500,500	99.5	498,500	99.8	497,000	99.8	455,650	99.1	470,700	97.5
Columbia Steel Shafting Co.	51,300	93.3	47,750	94.5	52,750	96.5	66,700	99.8	73,800	99.9
Witherow Steel Co.	77,100	88.6	68,000	92.7	74,900	87.4	94,250	88.5	123,000	71.0
National Tube No. 3	493,000	64.4	492,500	80.1	586,000	78.9	551,000	78.6	466,500	75.4
Universal Steel Co.	....	.....	....	.....	464,000	85.9	473,000	85.9	434,500	86.5
Average power factor	....	91.3	....	93.0	....	93.4	....	93.7	....	92.6

Total customers Dec. 31, 1924, 205,463. Total output 1924, 1,078,172,730.

These eighteen customers represent slightly less than 10 per cent of the output of the system.

TABLE XXV.—TYPICAL CUSTOMERS' RECORD

(No. 1. Columbia Steel Shafting Co., Rankin Plant
Clara St., Rankin, Pa.)
(*Reactive meters installed May* 21, 1924)

Date	Demand	Kilowatt-hours	Reactive kilowatt-hours	Ratio reactive kilowatt-hours to kilowatt-hours	Power factor	Per cent discount
May 22	151	1,250	1,400	1.1200	66.0	—2.38
June 21	123	22,800	35,300	1.5482	54.3	—6.66
July 23	133	22,050	17,800	0.8073	77.8	0.744
Aug. 21	123	17,700	10,400	0.5876	86.2	2.93
Sept. 22	165	30,800	11,300	0.3669	93.9	5.16
Oct. 22	151	28,250	12,900	0.4565	91.0	4.26

(No. 2. National Tube Co., Christy Park Works
Penny St. & B. & O. R. R., McKeesport, Pa.)

Date	Demand	Kilowatt-hours	Reactive kilowatt-hours	Power factor	Per cent discount
Feb. 29	2,019				
Mar. 31	1,822	276,500	366,000	60.3	—4.4
Apr. 28	2,044	610,000	748,000	63.2	—3.4
May 31	1,911	640,500	888,000	58.5	—5.05
June 30	1,933	493,000	586,000	64.4	—3.06
July 31	1,822	492,500	368,000	80.1	1.35
Aug. 30	2,222	586,000	457,000	78.9	1.02
Sept. 30	2,000	551,000	343,000	78.6	0.94
Oct. 30	1,711	466,500	406,000	75.4	0.12

(No. 3. Pittsburgh Screw & Bolt Co.
Preble Ave., N. S., Pittsburgh, Pa.)

Dec. 19	1,464	80,950	53,880	83.2	2.16
Jan. 18, 1924	1,469	200,700	130,680	83.8	2.31
Feb. 18	1,541	260,450	170,160	83.8	2.32
Mar. 18	1,579	273,800	174,000	84.4	2.47
Apr. 17	1,563	251,450	146,280	86.4	3.00
May 17	1,493	212,200	101,280	90.2	4.05
June 19	1,440	194,500	71,100	93.9	5.16
July 19	1,373	145,250	52,680	94.0	5.19
Aug.	1,269	130,700	69,840	88.2	3.48
Sept. 19	1,523	209,250	88,320	92.1	4.60
Oct. 18	1,523	208,800	101,160	90.0	3.97
Nov. 19	1,579	195,200	90,360	90.7	4.19

(No. 4. Pittsburgh Seamless Tube Co.
P. R. R. & 46th St., Morado, Pa.)

Jan. 24, 1924	2,300	768,500	555,000	81.1	1.60
Feb. 25	2,300	508,500	184,000	94.0	5.20
Mar. 13	.....	280,000	93,000	94.9	5.50
Mar. 24	2,350	165,500	57,000	94.5	5.38
Apr. 24	2,400	510,500	172,000	94.8	5.45
May 24	2,400	624,500	222,000	94.2	5.26
June 24	2,300	542,000	201,000	93.8	5.11
July 24	2,125	561,000	206,000	93.9	5.15
Aug. 24	2,200	690,500	271,000	93.1	4.89
Sept. 24	2,300	566,000	195,000	94.5	5.37
Oct. 24	2,450	530,500	209,000	93.0	4.88
Nov. 24	2,325	470,500	166,000	94.3	5.29

tomers, as they could afford to invest in the necessary metering equipment and usually had an engineering staff competent to maintain the full operating value of the corrective installation. Many of our customers, without making any additional investments, tuned their existing machines to secure the benefit of the discounts on their power bills and a number bought the corrective equipment to a degree warranted by the inducement afforded by the available discounts. Very few cases were encountered in which the customer did not readily undertake to secure the bonus, and no difficulty was found in instituting correction from engineering or public-relations aspects. The customers selected for the first installations were all large consumers who could earn a bonus readily, and we made no attempt to give penalties or bonuses to power customers generally. As a result we have paid larger sums for bonuses than we have taken in from penalties. These numerous and semi-experimental installations, however, have convinced us that it is advisable and feasible to institute the complete clause generally, and sufficient data are available to show how this can be done as a part of our normal business. As a result of the work done, our system now has a better power factor (72.8 per cent in 1922, 73.6 per cent in 1923, 74.7 per cent in 1924, without our own corrective equipment), and there have resulted other incidental good influences upon system operations. Correction undoubtedly has a bearing on the fact that during 1924 over 86 per cent of the energy generated was sold to customers. I do not think our method for securing correction can be instituted very successfully or economically for small-power customers or for those with combined light and power loads. It is very successful for large power users, however, and we believe it can be applied generally to this type of customer. Later it may be advisable to raise the power-factor value which will earn a bonus to more than 75 per cent.

62. Synchronous Apparatus on the West Penn System.—The article referred to in Art. 60 reported that F. D. Mahoney, commercial manager of the West Penn Power Company, stated his experience and opinions as follows:

Power-factor correction has long been in successful operation on the West Penn system, and as a result of our experience with the methods used we have become convinced it is easy to institute and simple to operate. We know it is very beneficial to ourselves and to our customers, for it results in better and cheaper service to customers and makes it more economical and simple for the utility to supply quality service.

On this system at our own expense we have installed eight 5,000-kva. and two 2,000-kva. synchronous condensers at convenient locations, and in addition a 30,000-kva. synchronous condenser for both corrective and regulatory purposes. These units in conjunction with the correction instituted by customers enable us to operate at a power factor of about 89 per cent on a system covering a big industrial area and having a peak load of over 160,000 kw.

Table XXVI.—An Analysis of a Customer Based on Rates of West Penn System

	80 per cent power factor	Leading power factor
Motor cost (11,550 hp.) complete	$ 330,000	$ 330,000
Condenser cost (5,000 kva.)	....	30,000
Total cost of equipment	$ 330,000	$ 360,000
Fixed charges at 12 per cent	39,600	43,200
Power Costs		
Average demand, horsepower	$ 8,500	$ 8,500
Average demand, kilovolt-amperes (80 per cent power factor)	7,926	
Average demand, kilowatts (unity power factor)	....	6,491
Consumption, kilowatt-hours	2,789,270	2,859,002
Credits for transformer ownership (10 per cent), kilowatt-hours	278,927	285,902
Credits for power factor correction (5 per cent), kilowatt-hours	....	142,951
Net consumption, kilowatt-hours	2,510,343	2,430,167
Primary block (70 hours use of demand), kilowatt-hours	554,820	454,370
Secondary block (115 hours use of demand), kilowatt-hours	911,490	746,465
Tertiary block (115 hours use of demand), kilowatt-hours	911,490	746,465
Excess, kilowatt-hours	132,543	482,867
Gross charge per month	52,017.70	45,407.31
Block discount	21,968.61	19,126.14
	$ 30,049.09	$ 26,281.17
Prompt payment discount, 2 per cent	600.98	525.62
Net charge per month	29,448.11	25,755.55
Annual power charges	353,377.32	309,066.60
Annual fixed charges	39,600.00	43,200.00
Total cost per year	$392,977.32	$352,266.60
Annual saving for power factor correction	....	$ 40,710.72

I doubt if one precise corrective method or rate clause can be used universally to secure correction, for even on our system we find many variable conditions existing. For example, voltage regulation may be so intimately associated with power-factor correction that it cannot be treated separately. Our general plan, therefore, it is to secure correction wherever possible and to use a minimum of complexity in metering, billing, and rate making. Our main object is to give good service at a reasonable profit and to have satisfied customers, and any corrective scheme must aid this plan.

On this system there are many mines which use synchronous motor-generator sets, and also there are a great many installations of synchronous motors for driving pumps and fans. We give an inducement to customers to use synchronous motors wherever profitable. In this connection the motor manufacturers should strive to replace the existing design of low-power-factor induction motors with equally good high-power-factor motors. The Wagner Electric Corporation, in my opinion, deserves great credit for bringing out a high-power-factor industrial motor.

Our rate for power customers provides for billing on a kilovolt-ampere basis and provides a bonus for a power factor of unity or better. The usual metering installation consists of a kilowatt-hour meter, a kilowatt-demand meter and a graphic-power-factor meter. The power-factor meter is used only intermittently and is simply a convenient check on the data obtained when power-factor contracts are first signed. With this system we have little trouble and it operates with the greatest simplicity. We are convinced that power-factor correction is good business for ourselves and for our customers and will continue to push it.

63. Some Results Due to Power-factor Corrective Methods.—Again referring to the article in question, J. H. Reniers, electrical engineer of the Pittsburgh Bolt and Screw Company, made an engineering and economic study of the plant and removed some group-drive installations. These consisted of one 75-hp., two 40-hp., and two 30-hp. motor installations, and 65 motors averaging about 3 hp. each were substituted for them. This move, in combination with some rearrangements of circuits, increased the plant power factor at the switchboard from about 60 to about 75 per cent.

TABLE XXVII.—USE OF MOTOR-GENERATOR SET FOR CORRECTION

Date, 1924	Synchronous motor input, kilowatt-hours	Direct-current generator output, kilowatt-hours	Motor-generator set losses	Total plant, kilowatt-hours	Plant load power factor
Sept	14,100	5,713	8,387	270,000	92.1
Oct	13,800	5,706	8,094	250,000	90.0
Nov	9,400	4,082	5,318	206,000	90.7
Dec	14,000	8,299	5,701	351,660	96.4
Jan	15,500	7,084	8,416	313,500	96.8
Feb	14,800	7,260	7,540	275,500	97.4
Mar	17,200	8,224	8,976	293,800	97.7
Apr	14,900	6,260	8,640	263,300	98.5

Two motor-generator sets were then located at the extreme ends of load circuits. There was ample opportunity to use the synchronous motors of the sets since they supplied direct-current crane service. As a result of correction, this company has received an average discount of 4½ per cent on power bills ranging from $2,000 to $4,500 per month for a period of 10 months.

Mr. Reniers stated:

> After this plant operates at full capacity, we should be able to get a discount of 5 per cent on our power bills and at the same time reduce the losses in our corrective equipment. Our total investment in corrective apparatus is about $18,000 and it is a simple matter to determine a balance between the cost of correction and the financial inducements offered for correction. We use two synchronous motor-generator sets at the load ends of the lines and obtain a power factor at our switchboard of from 90 to 95 per cent. Also we get a voltage of 440 to 445 at our machines, whereas heretofore this was about 438. This has meant better production. For example, on one machine the speed increased from 54 to 57 r.p.m. and this meant an increased production of 1,440 manufactured units per eight-hour day. Thus the indirect benefits we have received from correcting power factor and improving voltage regulation in themselves offset our financial investment. Correction offers no operating difficulties and we are well satisfied with the result we have obtained.

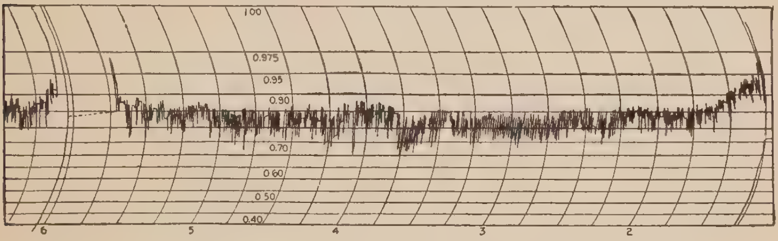

Fig. 54.—A good power-factor chart of a steel mill.

Other discounts of 4 per cent on power bills of $1,500 to $2,300 with power factors averaging 90 per cent are reported in the article.

The foregoing data appeared in the article by L. W. W. Morrow referred to in Art. 60. Figure 54 is representative of a good power-factor chart in a steel mill.

64. Benefit of Synchronous Motors.[1]—Study shows that this equipment, installed in large sizes, effects saving without preferential rate. In the case analyzed in the following article by Mr. Moore, the annual saving yielded a return of 15 per cent on increased investment.

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[1] Moore, L. J., Executive Engineer, San Joaquin Light & Power Corporation, Fresno, Cal., *Elec. World*, vol. 84, p. 733, 1924.

The installation of synchronous motors by consumers has been receiving much consideration from power companies in recent months. Various schemes for inducing the customer to install high-power-factor motors have been suggested. One factor which should not be overlooked in this connection is the saving to the consumer due to improved efficiency and improved power factor. That is to say, the saving gained is not all on the side of the power company. A study of the facts in the case shows that in many, if not in all, instances where motors are of reasonably large size, the change to synchronous motors can be justified without a preferential rate.

TABLE XXVIII.—RESULTS OF PRELIMINARY TESTS WITH INDUCTION MOTORS

	Kilowatt input	Kilovolt-ampere input	Power factor
Test on entire plant (including transformers)	686.0	925	74.2
Test on 200-hp. motor only	110.3	209	50.5
Test on 200-hp. motor and auxiliaries	193.0	349	55.0
Test on 500-hp. motor and auxiliaries	392.5	507	77.5
Test on 500-hp. motor only	328.0	387	85.0

TABLE XXIX.—LOAD WITH INDUCTION MOTORS AND WITH SYNCHRONOUS MOTORS

	KILOWATTS	KILOVOLT-AMPERES
With present induction motors:		
Case I. Operation of both motors	650	875
Case II. Operation of 500-hp. motor	500	605
Case III. Operation of 200-hp. motor	180	329
Case IV. Negligible load (under 50 kw.)		
With synchronous motors:		
Case IA. Operation of both motors	629	677
Case IIA. Operation of large motor	485	522
Case IIIA. Operation of small motor	174	315
Case IVA. Negligible load		

A large consumer on the system of the San Joaquin Light & Power Corporation was considering a change from induction motors to synchronous motors. The installation amounted to approximately 1,000-kva. connected load operating under very steady conditions in an ice-making plant. Service was rendered through three 250-kva. transformers, the consumer being metered on the high-voltage side of the transformers. Engineers of the power company made a careful investigation of the situation and obtained the interesting data here presented.

PRELIMINARY TESTS

First, a series of tests was made on the plant which gave the results shown in Table XXVIII. Based on these tests, the load in kilowatts and kilovolt-amperes with the present motors was determined for the four possible conditions of operation. The power factor of the various motors was determined from the above tests. An efficiency at full load of 88 per cent for the 500-hp. motor and an efficiency of 85 per cent for the 200-hp. motor were determined from the manufacturer's guarantees. The load in kilowatts and kilovolt-amperes, if the two large motors were replaced with synchronous motors operating at guaranteed efficiency and unity power factor, is shown in Table XXIX.

Necessary auxiliaries about the plant are included in each case.

The time the plant operated during the year 1923 with the various conditions of load was determined from the maximum-demand meter charts which show the load in kilowatts for 15-min. periods for the entire year. These charts showed the operations tabulated in Table XXX.

COMPARISON OF LOSSES

The use of synchronous motors will improve the efficiency of the plant and consequently reduce the amount paid for power in a number of ways. These will be taken up in detail and the quantitative saving based upon 1923 operations shown.

Table XXX.—Hours of Operation

	Hours
Case I. Both motors running	4,133
Case II. Large motor running	1,469
Case III. Small motor running	3,020
Case IV. Negligible load	130
Total (365 days' operation)	8,768

Table XXXI.—Transformer Kilowatt Losses

	Induction, Kilowatts	Synchronous, Kilowatts
Case I	10.45	6.69
Case II	5.62	4.19
Case III	1.61	0.69
Case IV		

Table XXXII.—Transformer Kilowatt-hour Losses

		Kilowatt-hours	
Losses with induction motors:			
Case I	$10.45 \times 4,133 =$	42,100	
Case II	$5.62 \times 1,469 =$	8,200	
Case III	$1.61 \times 3,020 =$	4,900	
Iron losses	$5.73 \times 8,760 =$	50,200	
			105,400
Losses with synchronous motors.			
Case IA	$6.69 \times 4,133 =$	27,600	
Case IIA	$4.19 \times 1,469 =$	6,200	
Case IIIA	$0.69 \times 3,020 =$	2,100	
Iron losses	$5.73 \times 8,760 =$	50,200	
			86,100
Saving in transformer losses with synchronous motors			19,300

A. Transformer Losses.—Power purchased by the consumer is metered on the high-tension side of the transformers, which means that he pays for transformer losses. The poorer the power factor of the load, the larger will be the kilovolt-amperes taken through the transformers and the larger the copper loss. The present bank of three 250-kva. transformers gives the copper losses for the various cases of load for both types of motors as in Table XXXI.

These losses times the number of hours the plant ran under the several conditions will give the comparative kilowatt-hour copper loss during 1923. The iron losses of the transformers will, of course, be constant in either case considered in this connection. The losses are given in Table XXXII.

B. Improved Motor Efficiency.—Table XXIX, giving the comparative kilowatts and kilovolt-ampere demand for the two types of motors shows that the kilowatt input for the synchronous motors will be less for the same output because of greater efficiency. This reduction in kilowatts would have amounted to that shown in Table XXXIII.

C. Elimination of Gear and Belt Losses.—The larger motor is geared to a compressor through gears, the efficiency of which is nearly 97 per cent, and the small motor is belted to a compressor, the belt efficiency being also nearly 97 per cent. The 3 per cent loss in each case will be eliminated by the use of direct-connected motors. This will amount to the value shown in Table XXXIV.

D. Necessity of Changing Transformers if Motors Are Not Changed.—The present bank of three 250-kva. transformers, with a total capacity of 750 kva., is overloaded more than 23 per cent when both of the present motors, having a combined demand of 925 kva., are in operation. These transformers must be replaced with three 333-kva. transformers before next summer if the motors are not changed, as further operation of the present bank at this overload is not safe. If synchronous motors are used, the demand will be reduced to 716 kva., which is well within the capacity of the present bank. The increased iron losses of the larger transformer will more than offset the reduced copper losses, adding 6,900 kw.-hr. a year to the transformer losses shown in Table XXXII.

Table XXXIII.—Saving with Improved Motor Efficiency

	Kilowatt-hours
Case I. (650 kw.—629 kw.) × 4,133 hr =	86,793
Case II. (500 kw.—485 kw.) × 1,469 hr. =	22,035
Case III. (180 kw.—174 kw.) × 3,020 hr. =	18,120
Saving in kilowatt-hours with improved motor efficiency	126,948

Table XXXIV.—Savings Gained by Eliminating Gears and Belts

	Kilowatt-hours
Large motor—output 472 kw. × 5,602 × 0.03	79,324
Small motor—output 935 kw. × 7,153 × 0.03	20,028
Saving in kilowatt-hours by eliminating gear and belt losses	99,352

Table XXXV.—Total Savings with Synchronous Motors

	Kilowatt-hours
A. Transformer losses, per year	19,300
B. Increased synchronous motor efficiency	126,948
C. Gear and belt losses eliminated	99,352
D. Transformer losses of larger bank	6,900
Total kilowatt-hour saving	252,500
Value at 0.89 ct. per kilowatt-hour	$2,247.25
Increased charges on larger transformers	118.00
Total annual saving to be effected with synchronous motors	$2,365.25

In addition to the increased losses of the larger transformers, the consumer will pay 11.8 per cent interest, depreciation, and maintenance on the increased value of the larger bank, which will be in the neighborhood of a thousand dollars. The increased charges will therefore amount to $118 a year more than the amount which is paid at the present time.

The consumer paid $33,547.56 for 3,762,000 kw.-hr. during 1923, or an average price of 0.89 ct. per kilowatt-hour. All of the kilowatt-hour losses with the present equipment, or, conversely, the savings to be made by the use of synchronous motors, will be evaluated at this unit price. These savings, which have been shown in the preceding paragraphs are given in Table XXXV.

SAVING EFFECTED

Quotations on synchronous motors with exciter and starting equipment to replace the present induction motors give a cost of approximately $15,500 f. o. b. Fresno, Cal. The second-hand or salvage value of the present induction motors on the open market will pay for their removal and the installation of the synchronous motors, making the total outlay not more than $15,500.

It will be seen that an annual saving of $2,365.25 yields a return of 15.26 per cent on the increased investment in synchronous motors in this case. Of this the consumer will, of course, have to pay depreciation and taxes, but even so, he still has a margin left which will pay a good return on his investment. It is not probable that the maintenance in the case of the synchronous motors will be any greater than in the case of the induction motors because the gears and belt have been eliminated.

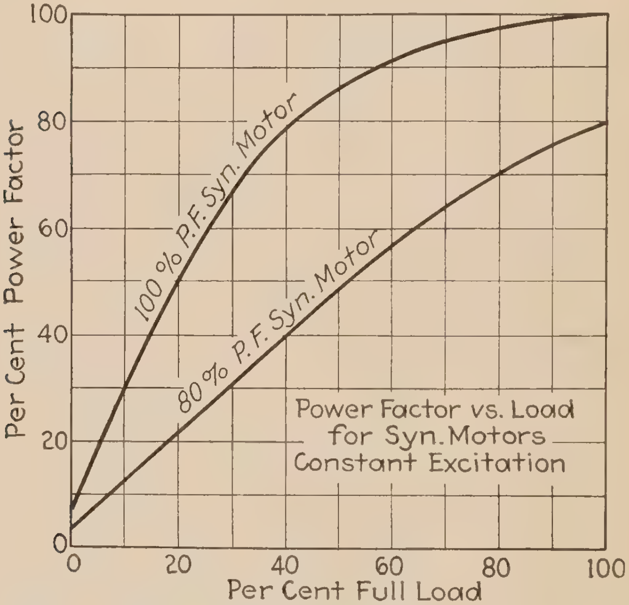

FIG. 55.—Power factor *versus* load for synchronous motors with constant excitation.

65. Some Characteristics of Synchronous Motors.—The following illustrations were presented by L. W. W. Morrow and were originally intended for the paper in Chaps. XVIII and XIX. They are placed in the present chapter because of the arrangement of the present text.

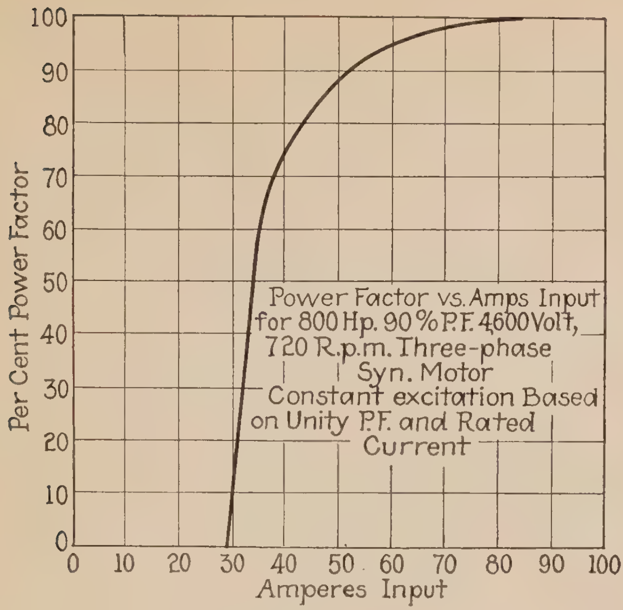

FIG. 56.—Power factor *versus* amperes input for synchronous motor.

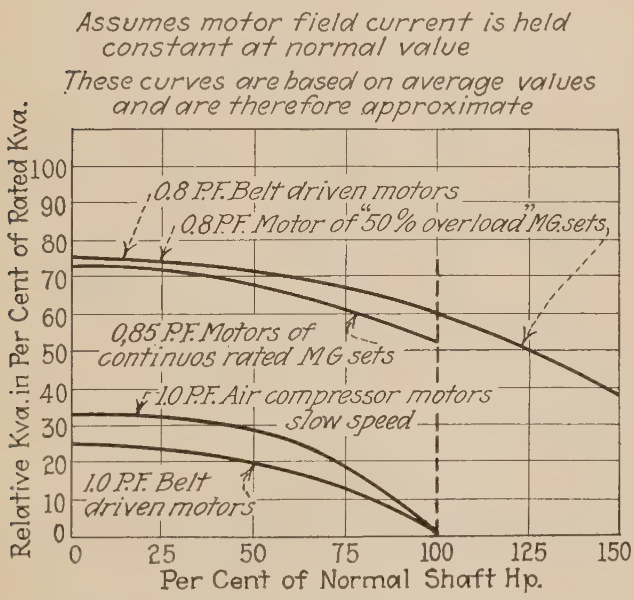

FIG. 57.—Reactive kilovolt-amperes available for power-factor correction at different horsepower outputs in synchronous motors.

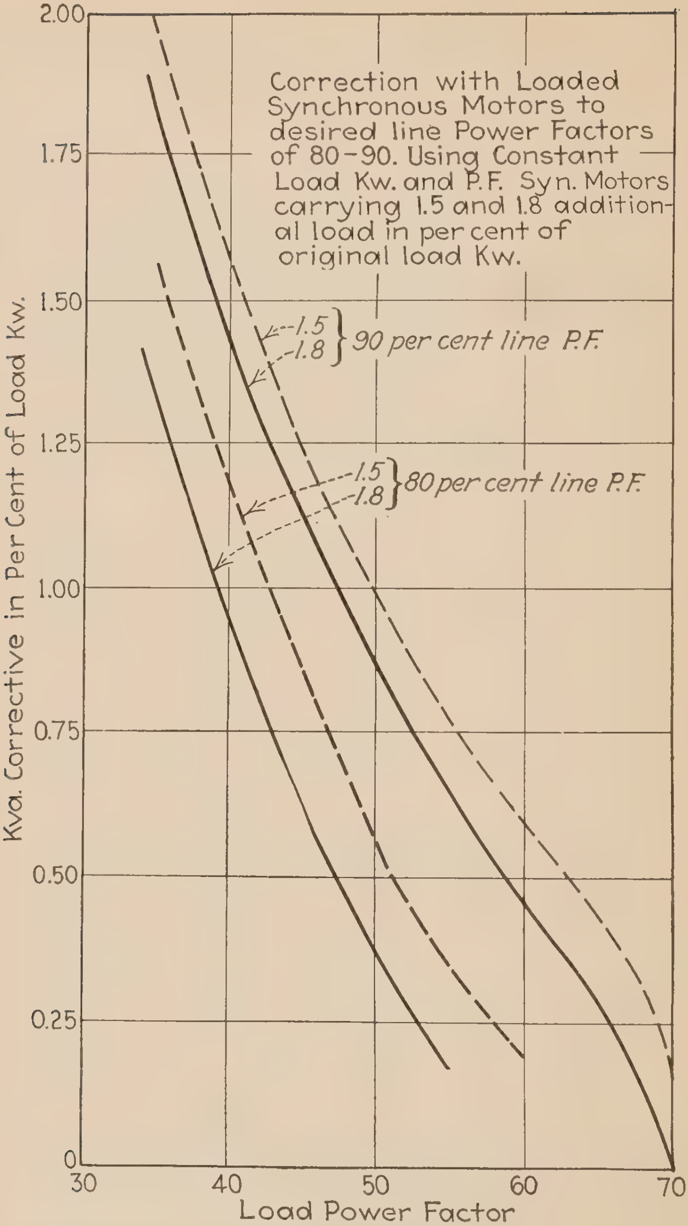

FIG. 58.—Correction with synchronous motors to desired line power factors.

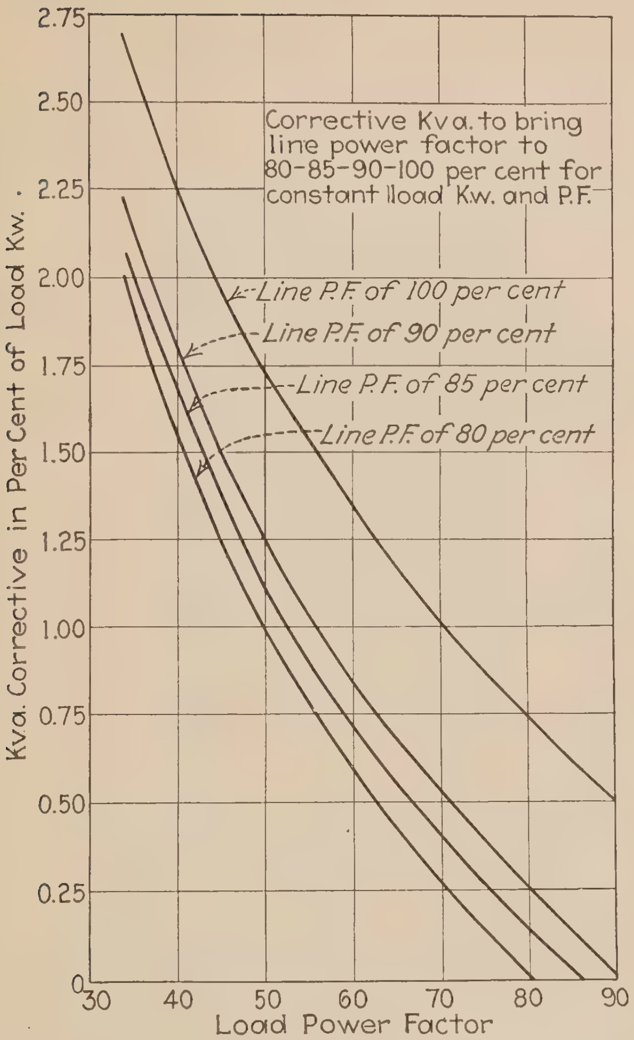

FIG. 59.—Corrective kilovolt-amperes to bring line power factor to desired values.

CHAPTER XII

STATIC CONDENSERS

The present chapter deals with static condensers in general, as used for power-factor correction where a synchronous condenser might otherwise be employed, or for correcting the power factor of the individual motor. The characteristics, advantages, limitations, mechanical construction and manufacture, and installation are treated in detail by W. A. DICK[1] who wrote the chapter especially for this volume.

66. Characteristics of a Static Condenser.—Fundamentally, a static condenser is a device for storing electrostatic energy in the field of a dielectric.

It stores energy when its voltage is increasing, and gives out energy when its voltage is decreasing.

In order to do this effectively, masses of dielectric must be subjected to electric stress. To use dielectrics efficiently, stress must be uniform and at highest safe point.

Means taken to accomplish this in practically all static condensers is to use large flat sheets of dielectric material to separate the conducting plates which are maintained at different potentials.

A static condenser acts as a non-conductor, or a very high resistance to a constant direct voltage, and a conductor while the voltage is varying. When voltage is applied and current flows, the condenser becomes a source of counter e.m.f. opposing the applied voltage. (When a condenser discharges through a resistance and inductance, the applied voltage of the condenser is equal to the counter e.m.f. of the resistance and inductance.)

Such a combination assembled in a case with leads brought out through insulating bushings constitutes a commercial unit.

A static condenser has no moving parts.

The kilovolt-amperes of a static condenser vary directly as the square of the voltage.

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[1] Supervisor of Correspondence Courses, Educational Department, Westinghouse Electric & Manufacturing Co.

The kilovolt-amperes of a static condenser vary directly within certain limits with the frequency.

The kilovolt-amperes of a condenser required for a certain correction are independent of frequency.

There is little or no variation with the temperature. The initial temperature is low—about 5° rise. Even with a variation between 20 and 80° the change in kilovolt-amperes is less than 1 per cent.

The efficiency is high. Losses are less than 5 watts per operating kilovolt-ampere when no transformers are used.

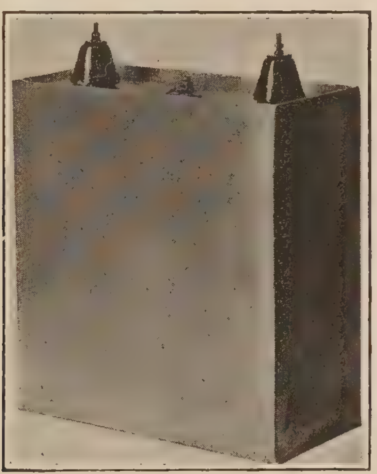

Fig. 60.—Static condenser unit, low voltage, single-phase.

When transformers are used, losses in the entire installation may be increased to as much as 35 watts per kilovolt-ampere, due to the losses in the transformers.

A static condenser draws a leading current. It is, therefore, applicable to systems with lagging power factor only.

Little or no attendance is required, and maintenance cost is negligible.

A complete condenser is usually made up of a number of individual units assembled to give capacity required. After installation, capacity can be reduced by cutting out some of the units by removing link connections.

Condensers are built so that they can be located anywhere inside a building or outside (Figs. 61 and 62).

When they go outside, a waterproof covering is made.

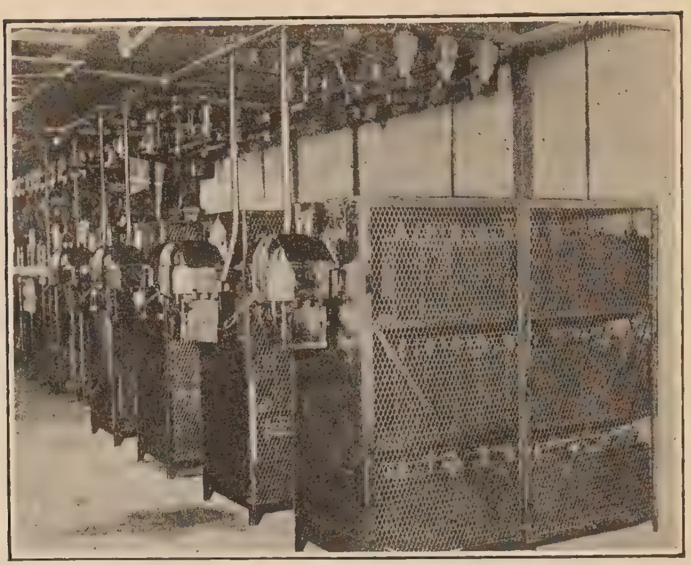

FIG. 61.—Installation of static condensers in a steel plant, total capacity, 480 kva., 2,300 volts.

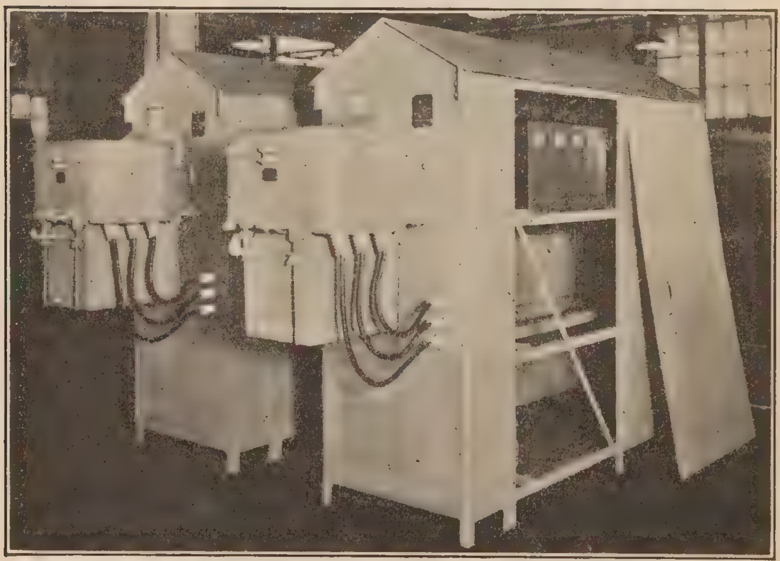

FIG. 62.—300-kva., three-phase, 4,600-volt static condensers, out-door mounting.

Condenser capacity per kilovolt-ampere at different 60-cycle voltages (Fig. 63).

The cost of a condenser increases as the voltage is reduced. This is shown by the following illustration: Approximately the same voltage stress per unit thickness of insulation is used in all condensers of a given type. Therefore, the volume of insulation per kilovolt-ampere is nearly constant. The size of a given kilovolt-ampere unit is the same for either 220, 440, 550 or 2,300 volts. The potential is supplied to the insulation by means of parallel plates arranged so that alternate plates have opposite polarity. Assuming that a mass of 21 lb. of insulation in a 2,300-volt unit is divided into 520 dielectric units by means of 521 metal plates; then a condenser of the same kilovolt-ampere capacity, but for 1,150 volts, would be divided into 1,060 dielectric units and 1,061 plates. A condenser for 220 volts would have 5,550 dielectric units and 5,551 metal plates. As the 21 lb. of insulation is subdivided into greater and greater numbers of units, each unit layer also becomes thinner. Thus the lower the voltage rating, the greater becomes the labor of building and the more costly the material on account of the decreased thickness.

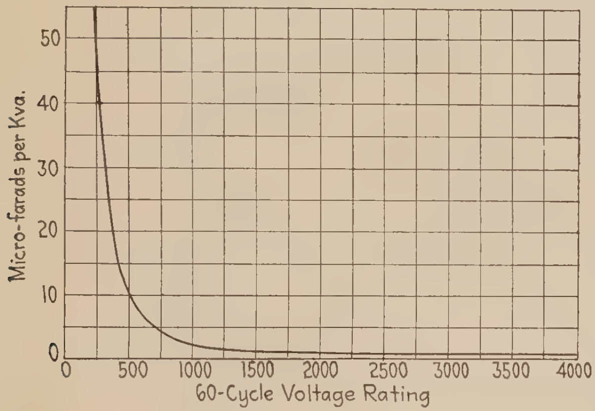

FIG 63.—Capacity per kilovolt-ampere for various voltages at 60 cycles.

67. Advantages of Static Condensers.

No moving parts.

Installed almost anywhere, indoors or out of doors.

Practically no attendance required.

Do not drop out if power goes off the line.

Noiseless.

Less floor space in smaller capacities.

Highest efficiency.

Maintenance cost practically negligible.

Easier, by merely closing or opening a switch, to put on or take off a line than a rotary machine.

Operates at very low temperature rise.

68. Limitations of Static Condensers.—Static condensers have certain limitations which are taken into account in applying:

Correction cannot be varied except by cutting in or out units.

Correction decreases with fall in voltage; ordinarily, however, the variations of voltage on any given line are so small that the change in corrective effect is negligible.

Corrective capacity is always leading and so is applicable only to lines with lagging power factor.

Takes more floor space in the larger sizes than other types.

Higher first cost in larger sizes, which may be offset by lower operating costs.

69. Mechanical Construction and Manufacture.—A complete condenser of a given rating is made up of an assembly of the proper number of standard condenser units. The unit ratings vary from 2 to 5 kva. and these ratings are determined by the most economical size for quantity manufacture. These units are assembled in angle-iron frames to the required numbers. The units are connected up to bus bars, and discharge resistances are usually permanently connected across the condensers to discharge them when they are disconnected from the line. A static condenser will hold a charge for a long time, and to make it safe for attendants it should be discharged when not in actual use. It is a good idea always to short-circuit a condenser anyway after it has been disconnected from the line, using an insulated wire for the purpose, before doing any work on it.

The resistances used are inductive and take very little energy.

Where the condensers are installed so that they are across a winding of some kind such as an induction motor, no resistance for discharging is needed. The angle-iron frames have protective coverings to suit either station or out-of-door installation.[1]

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[1] Method of shipment: Indoor frames, front plate assembly in one box; screens and rear end and side rails in second. Circuit breaker and units shipped separately. Outdoor frames, assembled except for condenser units and breaker.

All condenser units consist of many elements of insulation interposed between metal plates of opposite polarity. The thickness of these elements of insulation is chosen for each voltage rating so that the voltage stress per unit thickness is well within that which has proved to give reliable operation. Material used for these elements of insulation varies with the voltage rating, and in each case material is selected which gives the desired characteristics at a minimum of cost. The elements of insulation are stacked with metal plates which are connected to form terminals, alternate plates going to opposite terminals. The complete condenser is assembled in a sheet-steel case containing one opening for impregnation. The joints in the top of the case are crimped and soldered by a special process. The unit is then vacuum dried to remove the last trace of moisture, after which it is filled with oil. It will be interesting to outline some of the operations involved in the removing of all moisture and air which are the prime requisites for stability and life. Moisture is removed by volatilization when pressure is removed by a vacuum pump and a temperature considerably above boiling water maintained.

The evacuation of the moisture is made in two stages:

1. A primary evacuation to get rid of the bulk of the moisture occupying 60 to 80 hours of time.

2. A secondary evacuation for removal of the small residue remaining after (1) for 20 or more hours. The operation is continued until a moisture test shows proper dryness. Test is also made for leaks.

The oil is also carefully treated to remove any moisture and is then introduced while still hot into the condenser cases. After this the condensers are left on vacuum for at least 10 hours, to allow oil to work its way into the innermost crevices of the insulation. The condensers are then cooled while still connected to the oil tank so that oil is supplied to make up for contraction. Condenser is then plugged and given its final insulation test and is ready for shipment.

Oil in a static condenser is for the same purpose as oil in a transformer. This means that a condenser case does not have to be vacuum tight and that slight indications of oil on the outside do not mean any more oil in one case than in the other.

Tests.—All alternating current condensers for 2,300 volts and above are tested at 2¼ times rated voltage plus 2,000 volts for

1 min. Those for lower voltages are tested at 3.65 times their rated voltages for 1 min. Practically no failures occur in making these tests. Actual breakdown voltages range from 12,000 to 18,000 volts between terminals of the individual 2,300 volt units.

The dielectric or power losses are measured on every unit manufactured and must not exceed a certain maximum before the unit can be shipped. In this way the complete evacuation of moisture is checked.

The factor of safety of the insulation of these static condensers compares favorably with that of other types of electrical apparatus. As compared to paper-insulated cables, oil-impregnated tests, as given, are higher than used on such cables for same voltages, and cables are subjected to rougher handling and much higher temperature.

The LD condenser units have the following ratings:

220	440	550	volts	60 cycles	2 kva.
2,300	4,400	4,600 and 5,000	volts	60 cycles	5 kva.

Multiples of these are assembled to make the different capacity condensers.

The prime requisites of a static condenser for life and performances are high-grade materials and no moisture.

70. Installation.—In general, the best arrangement is to place at or near the source of the lagging current. However, this may work out best economically by installing either a few larger condensers centrally located or a large number of smaller units more widely applied.

The power factor of the entire plant may be corrected on the high-voltage side. This will benefit the line and all apparatus between the plant and source of power. The plant will not be much affected except that the regulation may be improved. In this case the lowering transformers have to carry the reactive component.

The power factor may be corrected on the low-voltage side, either by means of high-voltage condensers or by lower-voltage condensers built for the line voltage. In this case the improvement is the same as above, but in addition, the transformers are relieved of the reactive component.

The various arrangements of static condensers are as follows:

Group Correction.—1. Assemblies of units in frames making capacities of 60 to 300 kva. for 2,300, 4,000, or 5,000 volts, 60 cycles.

2. Assemblies having fairly large kilovolt-ampere ratings, made up of 2,300-volt units, operating in conjunction with transformers, for low-voltage lines.

3. Assemblies of 220-, 440-, or 550-volt units in frames in capacities of 24 to 96 kva.

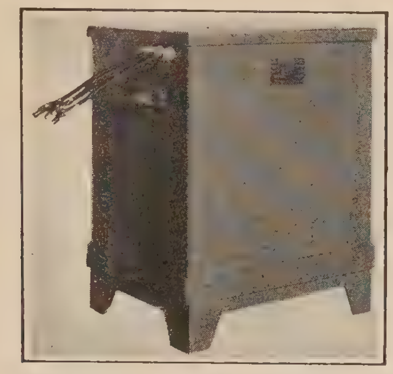

Fig. 64.—6-kva., three-phase, 220-, 440-, and 550-volt, static condenser cabinet outfit for individual motor application, floor mounting.

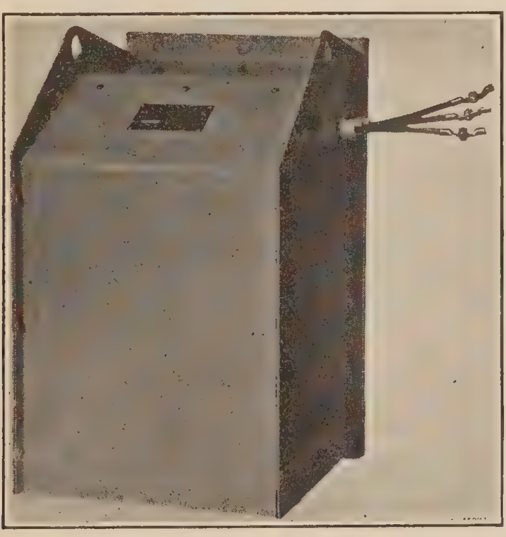

Fig. 65.—4-kva., two- or three-phase, 440-volt static condenser cabinet outfit for individual motor application, wall mounting.

Feeder Correction.—Sectional-type assemblies of 6 kva. or more to operate without transformers. For this application a sectional-type assembly has been developed, whereby sections of 6 kva.

may be assembled, one on top of the other, to the required capacity. These take up minimum space and are protected against dirt and injury.

Motor Correction.—Assemblies of 2 kva. for mounting alongside of autostarters at the individual motors or placed near group of small motors. For the individual application, two assemblies have been developed for wall mounting, rated at 2 and 4 kva. respectively.

These units are assembled for either two-phase or three-phase use. Larger units are made up of two or more of these in parallel or by combinations of the standard single-phase 2 kva. units.

The following table gives typical combinations of these with squirrel-cage induction motors and the results that will be attained.

TABLE XXXVI.—TYPICAL RESULTS OBTAINED WITH COMBINATIONS OF MOTORS AND CONDENSERS

Motor		Condenser, kilovolt-amperes	Approximate power factor		
Horsepower	Speed r.p.m.		Half load	Three-fourth load	Full load
3	1,160	2	98[1]	100	100
5	1,750	2	100	100	100
5	870	2	94	96	95
7.5	1,750	2	95	97	98
7.5	870	2	84	95	97
10	1,750	2	97	97	97
10	870	4	96	97	98
15	870	4	90	94	95
20	870	4	92	95	96
25	870	4	91	92	95
30	690	8	94	95	95
40	690	8	91	93	94
50	690	10	93	94	96
75	690	14	91	93	95
100	690	22	90	94	95
150	1,160	10	90	93	94
150	690	26	90	94	95
200	1,160	14	90	93	95
200	580	34	91	94	95

[1] Leading.

As to mechanical location, this can be made almost anywhere, the framework of the condensers being placed horizontally. It is not advisable to mount on the side or end. The circuit breakers should be accessible. The framework should be grounded according to approved practice. If there is not space available in a building, an out-of-doors type is available which consists of the standard unit furnished with solid covers making them waterproof instead of the regular expanded metal covers and with the out-of-doors type of circuit breakers. This arrangement can be installed outside of a building.

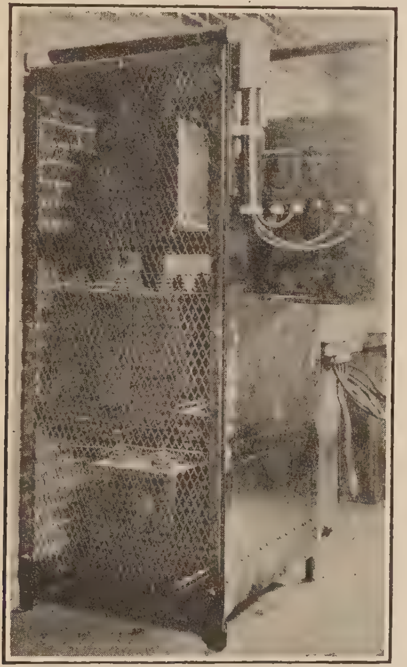

Fig. 66.—36-kva. static condenser, 2,300-volt, indoor installation.

It is quite often a happening that the load is metered on the high-voltage side of the power transformers. The condensers, if built for the voltage on the high side, can be directly connected to this circuit between the metering equipment and the power transformers. In this case, however, the power transformers will carry the same kilovolt-amperes as before.

The possibility of using condensers in the load side of the transformers with or without transformers can also be considered.

For wiring diagram for three-phase equipment, condensers connected direct to line, see Fig. 68. For wiring diagram for two-phase equipment, condensers connected direct to line, see Fig. 69.

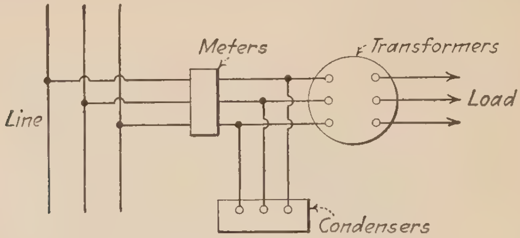

FIG. 67.—Condensers connected on the high-voltage side.

Condensers, as a rule, are equipped with oil circuit breakers for closing and opening the circuit. The exception is where condensers are connected to the line between a main switch or breaker and a motor or other load, and the condenser circuit is broken at the same time as the motor circuit.

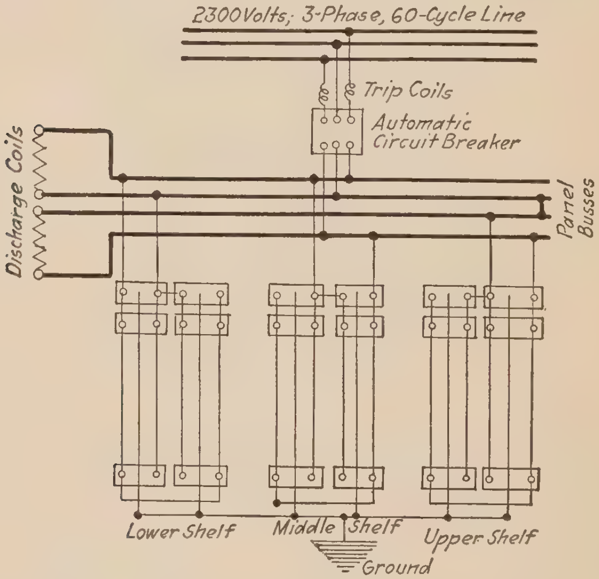

FIG. 68.—Wiring diagram for three-phase, 2,300 volts, delta connection.

Circuit breakers shipped with the condensers are of a type and rating suited to the circuit and condenser installation. The breakers can be:

1. Closed by hand.
2. Opened by hand.
3. Opened automatically by a series trip coil (overload) and have an inverse time limit to allow for motor starting, etc.

A no-voltage release is not recommended in ordinary cases, as the condenser does not then automatically return to service after an interruption. A no-voltage release can be furnished where conditions warrant.

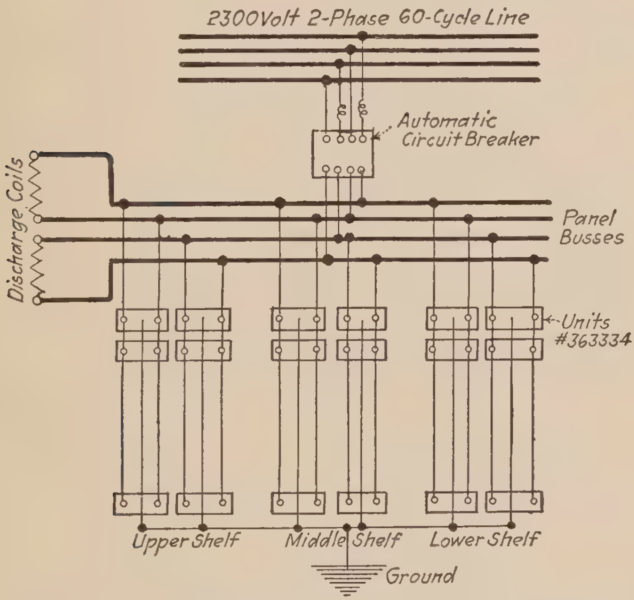

FIG. 69.—Wiring diagram for 2,300-volt, two-phase connection.

Condensers are made for standard voltages 220 to 5,000. For other voltages the standard 2,300-volt condensers should be used with transformers.

In some installations it may be advantageous to change the amount of reactive capacity because of varying loads due to changing conditions such as summer, winter, etc. It can be reduced by disconnecting some of the units by removing connecting links.

In order to maintain the power factor at as high a value as possible, it is necessary that the load factor of all motors under working conditions shall be high. In the case of induction motors, the chief points to comply with are:

1. The working speed shall be as high as possible consistent with satisfactory operation. The reason for this is that the smaller the frame the less the magnetizing or lagging current. Another way of putting it is that the power factor decreases as the number of poles in a motor increases. Again, the lower the frequency the better the power factor, *viz.*, a motor for 25 cycles would have 4 poles and for 60 cycles, 10 poles.

2. Direct-coupled motors running at very low speeds should be avoided. It would, however, manifestly be poor policy to sacrifice a mechanical and electrical application merely for power factor. The trouble that might result from using too high a gear or too small a pulley might offset a gain in power factor.

3. Ratings of motors installed should not be in excess of requirements; otherwise the motor would be running underloaded and at a low power factor.

4. After a plant has been operating long enough to get into steady production and after the machinery is well broken in, a management should be interested in conducting quite complete tests on the motor equipment to determine not only the average load but the nature of load of each particular machine. A study of graphic charts by a production engineer gives a good insight into the manufacturing conditions, while the same chart tells the electrical engineer what each motor is called on to do. Sometimes the investigation shows that smaller motors can be used and thus raise the power factor.

In applying corrective apparatus, the question is sometimes asked, "Should the average or peak-load power factor be used?" If the question of losses is under consideration, then it would appear best to make use of the average power factor. If capacity of system equipped to carry a given load is being determined, the power factor at time of peak load is, of course, the one to use.

The question may be asked, "Can static-condenser assemblies be connected in series for operation at high voltages?" The answer is that it is not advisable to do this, although the electrical performance as a condenser will be perfectly satisfactory. To do so, however, involves insulation for the higher voltage. There is also difficulty at times in getting a combination to give the exact voltage required. Condensers should be built for an exact voltage as the kilovolt-amperes vary so fast with changes in voltage.

Fuse Requirements.—When static condensers are designed with a high working stress, the condensers occasionally become short-circuited due to failure of the insulation, and fuses are required.

Since LD condensers are designed with a low working stress, the possibility of failure of the insulation is very remote and occurs only when some error is made in the actual building of the unit. To date, no Westinghouse condensers have failed due to weak insulation, and therefore, it is obvious that the unnecessary expense of individual fuses has been eliminated.

The advantages of fusing condenser units are positive isolation of defective units and means of cutting out units, but there are disadvantages also, as annoyance of frequent renewals, cost of renewals, added attendance, and so forth.

The individual fuse idea might be of some use in isolating defective units in the case of a star connection where a short-circuit in one unit will increase the line current only about 75 per cent. A breaker properly set, with dashpot, would do equally as well. Westinghouse has abandoned the straight star connection. Where it is desirable to use a star connection, a special circuit is used called a "double neutral trip scheme." This provides a positive tripping of the circuit breaker for a short-circuit in any unit or even for a removal of two or three units from any phase which would cause an unbalanced voltage and set up current in the transformer.

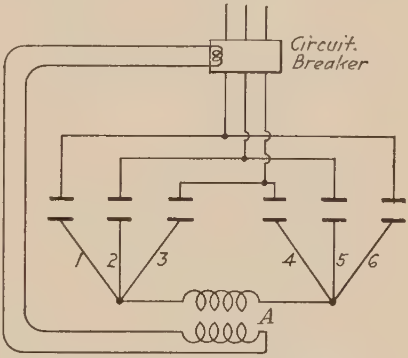

FIG. 70.—A possible arrangement of connections.

A possible arrangement of connections (Fig. 70): *A* is an instrument transformer. A breakdown in any one of the circuits 1, 2, 3, 4, 5, 6 will cause a difference of voltage so that current will pass through *A* and trip the breaker.

In order to cut out individual units by pulling fuses, it is necessary to take the condenser off the line. It is about as easy to cut out a unit with the connector scheme. Take a 300-kva. frame containing 60 units. Assume that it is desired to cut out six units from each phase. In the case of fuses it would be necessary to remove twelve fuses, while the connector scheme it is necessary to remove only three links. It is seldom necessary to do this anyway.

When a fuse blows, a large amount of stored energy from the rest of the condenser is dissipated at the fuse. This makes the performance of the fuse somewhat uncertain, especially in the case of delta connections where the fuse is called upon to open a large short-circuit current.

Due to the fact that if the breaker on the condenser is closed and opened and then closed again when the voltage on the condenser is equal and opposite to the applied voltage, the rating of the fuse must be extremely high in comparison to the normal current. Even with the most liberal rating, great trouble is experienced with fuses blowing when the condenser is switched on and off.

When fuses are not used, it is possible to screen the condenser. It is not necessary to provide space for getting at the condenser except on one side. The breaker being external to the condenser is, of course, accessible for repairs without disturbing the condenser. Except for a unit failure or change of links, it is not necessary to remove the screens.

Reactors.—The Westinghouse type of condenser is built in such a way as to limit the short-circuit by the fusibility of the foil conductors. In addition, circuit breakers are chosen with suitable interrupting ability.

It is not evident, therefore, that the reactor is justified as a power-limiting device. In any case, the reactor could be abandoned if a proper circuit breaker is used. As for the condenser exploding and throwing oil, this cannot happen on a delta outfit unless the breaker at the condenser or other breakers fail, as the condenser such as 2,300 volt, 5 kva. will handle a 5,000 amp. short-circuit for 15 or 20 cycles without opening up.

It is sometimes claimed that reactors are necessary under certain resonant conditions with harmonics; in other words, that if static condensers alone were connected to a line which already had some harmonics, these harmonics might be exaggerated by them. The facts in the case are these: This exaggeration of the harmonics is possible but likely to be very infrequent.

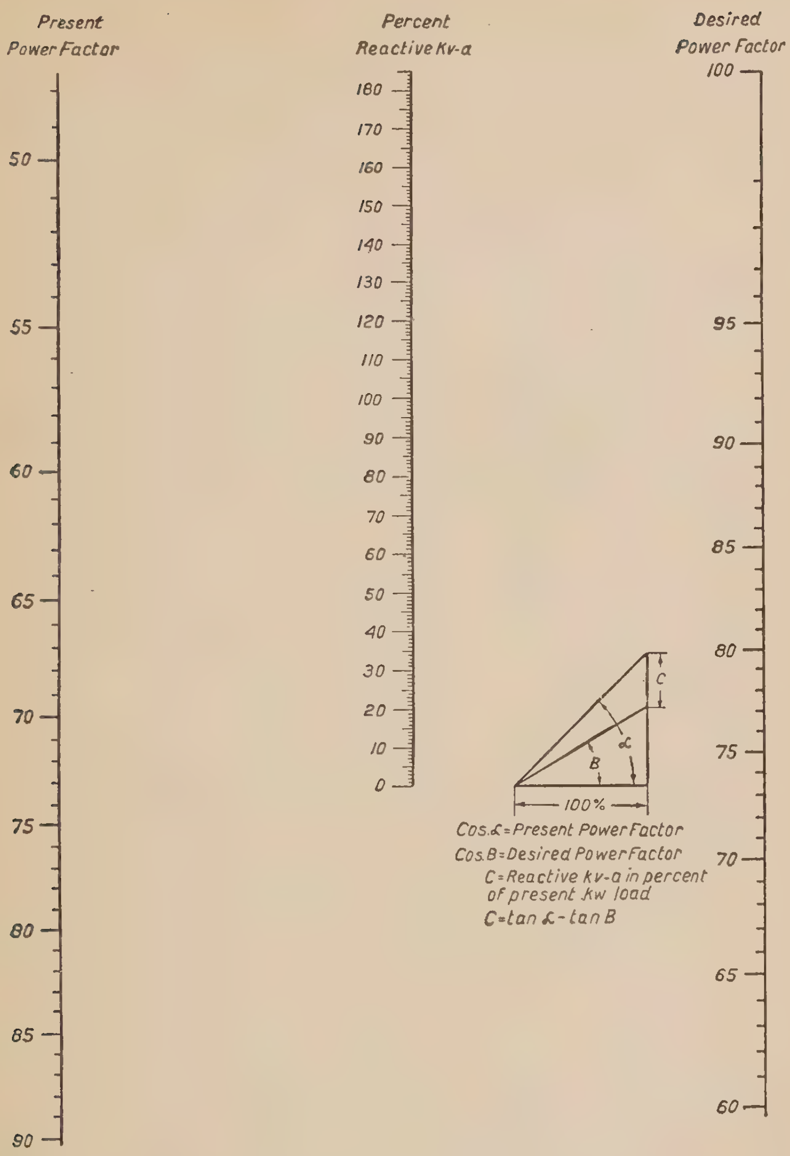

FIG. 71.—Reactive kilovolt-ampere calculating chart. To find the per cent reactive kva. necessary to raise the power factor from "Present Power Factor" to "Desired Power Factor," lay a straight edge across the chart connecting these two values. Read the "Reactive Kv-a." in per cent kilowatt on the middle scale. *Copyrighted* 1921, *Westinghouse Electric & Manufacturing Company.*

Westinghouse condensers will perform properly with or without reactors and they can be furnished when needed. No change in the condensers themselves is required.

With normal wave forms, especially at the load end of the lines, there is no need for reactors. Condensers are always installed at the load. Where poor wave forms are experienced in special cases, and where wave form cannot be improved, the use of reactors becomes justified. This necessitates a careful study of each case.

71. Examples.—Results obtained in practice are shown by the following example of a typical installation: A pressed-steel works making heavy punched-, pressed-, and drawn-steel products had 60 motors in all ranging from ¾ to 250 hp. For direct-current current required by hoist and magnet, a 100-kw. rotary converter is used. Current is three phase, 60 cycle, 440 volts. Initial power factor about 35 per cent increased to 95.4 per cent.

This was accomplished:

1. By remotoring.
2. By adding corrective apparatus.

It was found by making a test of power requirements of the different machines that many of them were overmotored on basis of these results. It was decided to change the motors to those with capacity for actual requirements. After this had been done and the rotary-converter operation changed somewhat, the power factor had increased to 68 per cent.

Investigation of costs showed that static condensers were most economical for additional correction, and a 60-kva. unit was installed. This brought the power factor up to 95 per cent.

The total cost (1924 figures) of the improvements were:

Remotoring	$2,935.27
Static condensers and installation	2,111.46
Total	$5,046.73

The improved power factor resulted in savings such that the changes and new equipment were paid for in 26 months, and after that period, the power bills were reduced an average of $530 per month over what they would have been with the original power factor.

This represents a greater saving than would ordinarily be expected because of the abnormally low power factor to start due to the overmotoring. In a few cases, it was found possible to replace 25-hp. motors with 7½-hp. motors.

CHAPTER XIII

CORRECTION OF THE INDIVIDUAL MOTOR WITH STATIC CONDENSERS

As a general principle, the logical place to correct an effect arising from any cause is at the location of that cause, although there may be practical reasons for partially correcting such effects at other locations. Since the induction motor is the principal cause of low power factor (the effect), either the induction motor should be applied only to such loads as may be suited to the operating characteristics of this type of motor, it should be replaced by some more suitable type of motor, or some means should be combined with it to increase the power factor of the combination. In the present chapter, written especially for this volume by P. B. VALLÉ,[1] the benefits of a static condenser in combination with an induction motor are explained.

72. General.—The individual static condenser is designed for the correction of the power factor of the individual induction motor, and is applied at the terminals of the motor. It is, therefore, designed for operation at the voltages most common in commercial practice—220, 440, and 550 volts, and usually for 60-cycle frequency. They may be obtained in units of ¼- and ½-kva. correction at these voltages, and are so made that any combination or multiple of these capacities may be made readily to apply to any given motor from ½ hp. to many hundred horsepower. Figure 73 shows a typical 2-kva. unit.

The capacity in microfarads necessary to give 1-kva. correction (furnish one leading reactive kilovolt-ampere to the system) varies inversely with the square of the voltage and inversely with the frequency. Thus, for 220-volt, 60-cycle service, about 55 mf. per kilovolt-ampere are required, while for 2,200-volt service (the voltage often employed on group condensers), only 0.55 mf. is required.

Of course, less insulation is employed for 220-volt service than for 2,200-volt service, but even so, the individual condenser costs approximately twice as much per kilovolt-ampere for 220-volt service as does the 2,200-volt group unit, while for 440- and 550-volt service, the cost is approximately the same per kilovolt-ampere as for the 2,200-volt group type.

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[1] Chief Engineer, National Electric Condenser Co.

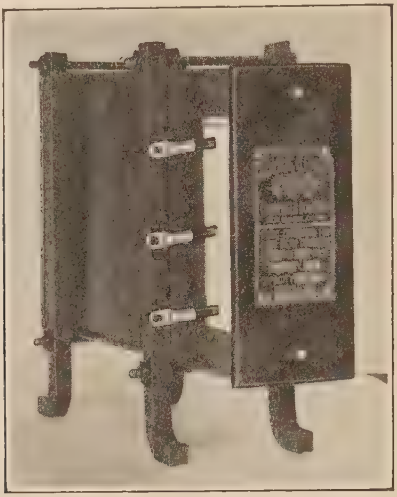


FIG. 72.—½-kva. static condenser for individual-motor application.

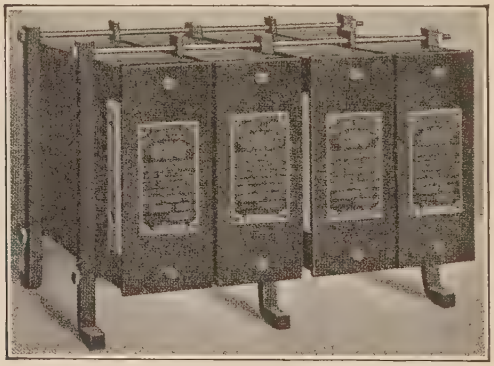


FIG. 73.—2-kva. assembly of static condensers for individual-motor application.

In spite of the difference in cost, the application of 220-volt individual condensers is often much more economical than for other less costly forms of correction.

The application of the individual condenser requires a study of the plant where the proposed installation is to be made. This fact is necessarily brought about by the unique savings obtained by the use of this type of apparatus, as will be hereinafter described.

The very fact that an engineering survey is necessary for the proper application of individual condensers has an extremely important secondary effect in bringing to light uneconomical plant conditions and suggesting their remedy, such as motor changes, changes on system of distribution or control, etc.

In discussing the advantages to be gained by individual correction, and the method of figuring their application, it is well to review fundamentals.

Power factor is the ratio between the current used for power in a system and the current actually delivered in a system.

The current delivered in a system is the vectorial sum of the current used for power and the current used for magnetizing the motors, transformers, and other inductive apparatus in the system.

The efficiency of a generator, transmission system, or distribution system for a given load is a function of the square of the current delivered in the system. This is true of every piece of apparatus from the generator to the last inch of motor lead wire.

The capacity of a generator, transmission line, or distribution system is a direct function of the current delivered in the system.

The following characteristics of induction motors should also be remembered:

1. An induction motor operating at rated load and voltage is, in general, operating at higher power factor and higher efficiency than when operating at less than rated load.
2. A motor operating at lower than rated voltage is lower in efficiency for a given load than if it were operating at rated voltage. This is particularly true of motors driving a pulsating load, such as a loom, automatic press, reciprocating pump, etc.
3. A motor operating at lower than rated voltage operates at slightly lower speed than at rated voltage.
4. A motor starting with a lower voltage than its rating has a decreased starting torque compared to what it would have at a higher voltage.

In considering the effects of the application of any corrective apparatus, the *location* of the apparatus must be taken into account. Corrective apparatus will correct power factor only from the point of its installation back to the generator. It will not correct power factor or the conditions arising therefrom from the point of its application *forward* to the motor or other inductive apparatus which is the cause of the low power factor. Thus a piece of corrective apparatus placed at a plant's meter board will correct the power factor of the plant back through the transformer to the generator, but in no way affects the power factor or the effects of low power factor *forward into the plant itself.* Similarly, correction *at the motor terminals* will correct the low power factor and its effects all the way from the terminals of the motor though the plant itself and back to the generators. Thus with individual motor correction, not only will the generating and transmitting system be given the benefit of the corrective apparatus, but also the benefits are shared by the entire plant itself. In other words, the full benefit of power-factor correction can best be obtained by correction of the power factor at its source—the individual induction motor.

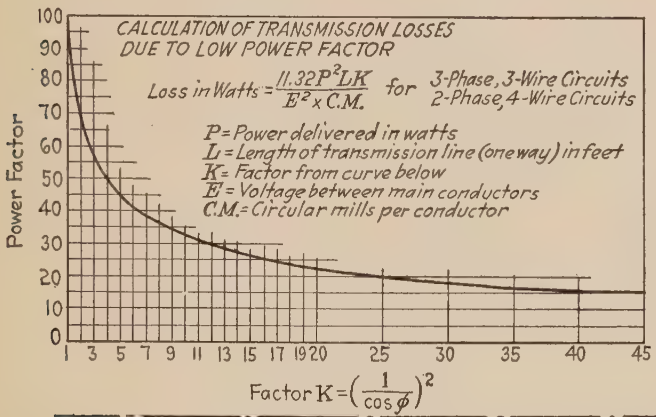
The question is sometimes asked: "What is the life of an individual static condenser?" Since the experience of the National Electric Condenser Company with this type of apparatus dates back only five years, no prediction can be made which is based on experience.

It should be remembered, however, that the insulation between plates of the condensers is of such a nature as to be extremely stable under the influence of the electrical field, and since precaution is taken in their manufacture to exhaust all air and moisture from this insulation, and hermetically to seal the condensers, it can be seen that the insulation functions under the best possible conditions for long life, and it is, therefore, reasonable to assume that the life of these condensers certainly will be as long as that of other apparatus in which the insulation comes in direct contact with air and moisture as it does in a motor.

Referring back to the fundamentals previously mentioned, the following articles give the results to be expected from correction of power factor by means of static condensers at the terminals of the individual motors.

73. Increase in Power Factor.—This is reflected by a direct saving in the monthly bill for power, in such cases where a clause exists in the rates of the utility supplying the energy which either penalizes low power factor or else gives a bonus for high power factor.

74. Increase in Efficiency of Distribution System.—Since the efficiency of a distribution system for a given load is a function of the square of the current delivered to it, any device which will reduce the current will greatly increase the efficiency. The current flowing in a system is inversely as the power factor of the system. System efficiency, therefore, is inversely as the square of the power factor. This is well understood by the accompanying curve, Fig. 74. From this curve the losses in distribution lines in a plant may readily be determined. From inspection of the curve, it will be noted that at 50 per cent power factor the losses are four times what they are at unity, and at 20 per cent power factor they are twenty-five times as great as at unity. While it is true that such low power factors are not generally found in a plant taken as a whole, yet it is not uncommon to find one of several individual motors in a plant operating at 20 per cent power factor. Cases have been encountered where the



Example · Given a load of 20 Kw. at 220 volts delivered over a 3 φ No. 4 B. & S. Line 200' long. (No. 4 B. & S. wire = 41,740 C. M.)

$$\text{At 50\% power factor } L = \frac{11.32 \times (20{,}000)^2 \times 200 \times 4}{(220)^2 \times 41{,}740} = 1793 \text{ watts}$$

$$\text{At 95\% power factor } L = \frac{11.32 \times (20{,}000)^2 \times 200 \times 1.108}{(220)^2 \times 41{,}740} = 497 \text{ watts}$$

The line loss saving due to raising the power factor from 50% to 95% is therefore 1296 watts, or 72% of the original loss

Fig. 74.—Transmission-loss chart.

loss in the distribution line is greater than the power actually used by the motor. This increase in distribution-line efficiency is a direct saving for the plant in kilowatt demand and kilowatt-hour consumption, appearing as such in their power bills. It is well to stress again at this point that this and most other forms of saving mentioned in this chapter can be best obtained through the use of the correction of power factor at its source, by means of individual static-condenser correction.

75. The voltage regulation at motor terminals is a function of the current flowing in the system. This has an important effect on motor operation and efficiency as will be mentioned later. It is often convenient to consider the individual condenser as a sort of *generator* of *magnetizing* current *at* the motor terminals, where the magnetizing current is most needed, thus relieving all other parts of the system of the necessity of generating, transmitting, and distributing this magnetizing current to the motors corrected.

76. Better Motor Efficiency.—Better voltage at motor terminals means better motor efficiency for a given load. This means additional kw. demand and kw.-hr. consumption savings reflected in bills for power. In general, they depend on the circuit characteristics and the magnitude of the voltage drop. They also depend on the character of the load, being less for a steady load (motor-generator set, centrifugal pump) than for an uneven or pulsating load (loom, knitting machine, etc.). Savings per unit of work produced have been as high as 15 to 20 per cent, these savings being measured practically at the motor terminals so that no line-loss saving was included. Savings of 5 to 10 per cent are not uncommon.

77. Slightly Increased Motor Speed.—Better voltage at motor terminals means slightly increased motor speed and sometimes better production. The direct effect of increased production from this source is slight, however, except in centrifugal processes where the output varies as the cube of the speed. However, the item of increased production attained through the application of individual condensers is often of greater value to the manufacturer than savings in power bills, large though these latter may be. It is generally recognized that the increased production is brought about through smoother motor operation rather than by increased speed. The magnitude of the increased production is almost impossible to predict, but it has occurred again and again where application of individual condensers is made, and is too important an item not to mention in a discussion of the effects obtainable with this class of corrective apparatus.

78. Increased Starting Torque.—Better voltage at motor means an increased starting torque. This is very important in figuring motor changes. It is well known that a motor corrected with individual condensers will start and carry a larger load than the same motor without condensers.

The importance of correct motoring has no doubt been fully discussed elsewhere in this book, but the above mentioned assistance to correct motoring should not be lost sight of. Power factor may be most economically corrected by motor changes and substitutes, but there is always a point in this direction beyond which it is not possible to go.

79. Conclusions.—It is obvious from the foregoing that certain very distinct advantages accrue through the use of individual condensers at the motor terminals. Other advantages of individual correction are its flexibility and its easy financing by the customer. It should not be thought that the use of individual condensers at the motor terminals implies that *every* motor in the plant must be corrected. This is not the case. Only those motors should be corrected which need correction. A large motor operating at full load will have inherently good power-factor characteristics. Such motors may be left alone, and attention turned to other motors operating necessarily under more adverse load conditions.

It is perfectly obvious that on account of the unit type construction of the individual condenser a customer need purchase only a part of his correction at one time and start in immediately to receive the benefit from it. Correction may then be added as the customer finds it convenient to finance its purchase, until the most economical point is reached.

To sum up, the following are the special advantages to be expected from individual type correction:

1. Decreased kilowatt demand and consumption due to better distribution system and motor efficiency.
2. Increased production and sometimes better quality of product.
3. Possibilities of better motoring.
4. Flexibility of application.
5. Ease of financing.

These advantages must be figured as accurately as possible for each proposed installation and credited to the type of corrective apparatus possessing them. It must be remembered that the individual unit as constructed by the National Electric Condenser Company is an extremely efficient piece of apparatus in itself, its losses not exceeding one-fourth to one-half of 1 per cent of its rated capacity.

A characteristic example of the savings that may be obtained through the use of the above condensers properly applied to the individual motor is found in the case of a silk-hosiery knitting mill which has been operating at a power factor of 33.5 per cent.

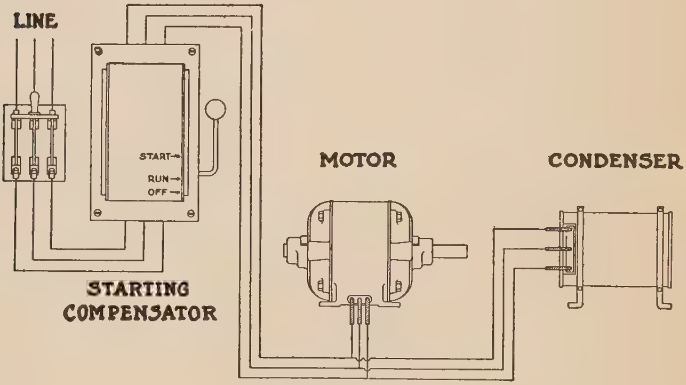


Fig. 75.—Method of connecting.

Condenser capacity sufficient to raise the power factor to 80 per cent was applied at the individual motors in this factory with the following results:

1. Reduction of 45 per cent in the billed demand (this included elimination of the power-factor penalty and also the kilowatt-demand savings).

2. A saving of 26 per cent in kilowatt-hour consumption due to a reduction in line losses and better motor efficiency following the improved voltage conditions.

3. A faster and smoother operation of knitting machines resulting in an increased output and a better quality of product, chiefly because of less thread breakage.

The factory owners in this case state that the National condensers paid out their initial cost in a very few months from the savings made in reduced bills for power and from increased machine output.

The individual unit is extremely easy and inexpensive to install. The condenser is connected directly at the motor terminals between the motor and the motor switch or compensator. When the motor is shut down, the condenser also shuts down and discharges immediately through the motor windings, making it an exceptionally safe piece of apparatus (see Fig. 75). No discharge resistances, switches, fuses, or other accessories are necessary. The condenser simply is placed in some convenient location near the motor it is to correct, and the connections are quickly made. There are no moving parts to wear or be affected by dirt, oil, dust, or moisture. It then operates without further attention of any kind.

CHAPTER XIV

CAPACITORS

The present chapter, written exclusively for this volume by R. H. CARLTON,[1] deals with static condensers as substitutes for synchronous condensers and also for the individual and group correction of the power factors of induction motors. Some applications and the savings gained thereby are illustrated and given.

80. General.—The economical operation of a generating and distributing system is dependent on the maintenance of a relatively high power factor. The reduction in the output of generators, transformers, and distributing feeders, as well as the increase in heating losses and impaired voltage regulation resulting from low power-factor loads, is well recognized by central stations. In many cases on large generating systems, this increment of load has warranted the installation of a synchronous condenser in the substation or, if an attendant is available, at the point of application of the reactive load, to overcome the detrimental effects of a low power factor. In order to meet the demand for a condenser which would provide similar corrections for comparatively small loads having low power factor, and which would not require an attendant, the capacitor was developed.

Capacitors for 2,300-volt service consist of a number of capacitor units, a reactance for damping out the higher harmonics in the voltage wave which would affect the corrective capacity of the units, a discharge resistance for draining the capacitor charge when disconnected from the line and an oil-circuit breaker for the control of the equipment. For 220-, 440-, and 550-volt service, a transformer is provided to step up the supply voltage to 1,200 volts for the units in order to permit more economical use of the active material in the capacitor unit.

The number of capacitor units included in an equipment is directly proportional to the capacity required. The unit is treated under vacuum to withdraw all moisture and is immersed in oil, and the container is then hermetically sealed to prevent possible absorption of moisture from the air. The units are mounted on a rack as shown in Figs. 76 and 77. They are connected in parallel across each phase, one terminal being connected directly to one leg while the other is connected to the other leg of the phase through a fuse as shown in detail in Fig. 77. The purpose of the fuse is twofold: first, to provide protection for the units against the application of an abnormal potential; second, to provide a means of automatically opening the connection of any unit to the bus on the rack in case of failure of the unit, making it unnecessary to disconnect the entire equipment. The connections for a 2,300-volt equipment are shown in Fig. 78.

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[1] Manager, Lightning Arrester and Voltage Regulator Division, Central Station Department, General Electric Company.

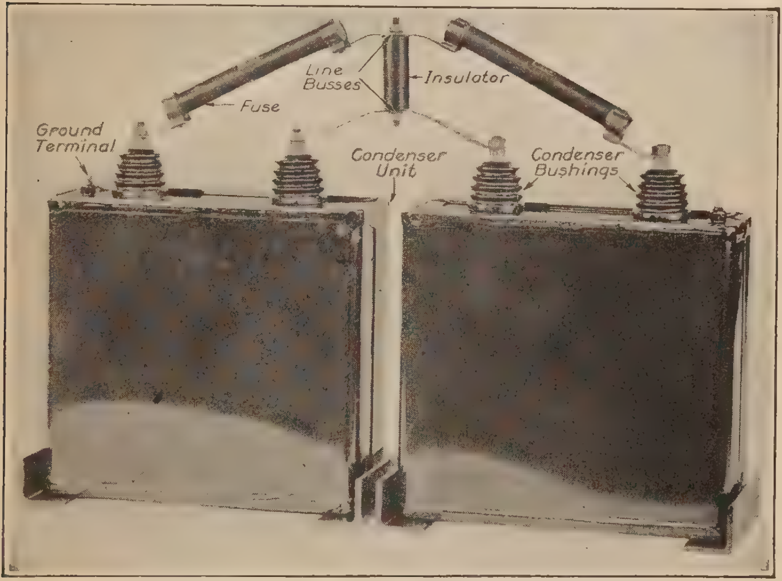

FIG. 76.—Detail of assembly of capacitor units on rack.

As mentioned before, with equipments designed for applications on 220-, 440-, or 550-volt circuits, a transformer is supplied for stepping up the supply potential to 1,200 volts for the capacitor. If the capacitor units were designed for direct installation on circuits of these voltages, a much greater active area would have to be provided in order to handle the increased current and this would result in increased cost. By applying 1,200 volts to the unit, however, the active material is used more economically, as the active area is reduced and ample factor of safety in insulation is retained by increasing the number of paper laminations between the plates and by the use of the oil. The connections for a low-voltage equipment are shown in Fig. 79. The transformer is designed with an inherent reactance of such value as to dampen any higher harmonics that may be set up when the capacitor is connected to the line. The transformer also provides a path for discharging the capacitor units when the equipment is disconnected from the line. Consequently, separate reactors and discharge resistances are not required with low-voltage capacitors.

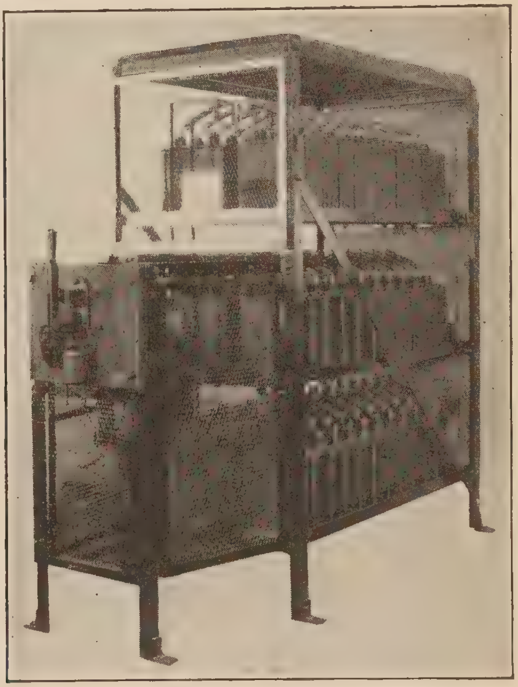

Fig. 77.—Three-phase capacitor.

For the correction of power factor on circuits exceeding 2,300 volts, except 4,000-volt, Y-connected, three-phase circuits, a transformer is furnished depending on the ratio of transformation required to step the voltage down to 2,300 volts; each equipment includes a suitable oil circuit breaker provided to control the equipment from the line side of the transforming apparatus. On 4,000-volt, Y-connected, three-phase circuits, 2,300-volt capacitor units are used in Y-connection with a series reactor.

The capacitor is an extremely efficient device, the losses in the 2,300-volt equipments being less than 1 per cent of the rated kilovolt-ampere capacity. The losses in the low-voltage equipments are increased to 3 per cent due to the use of transformers. The low losses of the capacitors should be taken into consideration when this type of equipment is compared with other apparatus designed for power-factor correction.

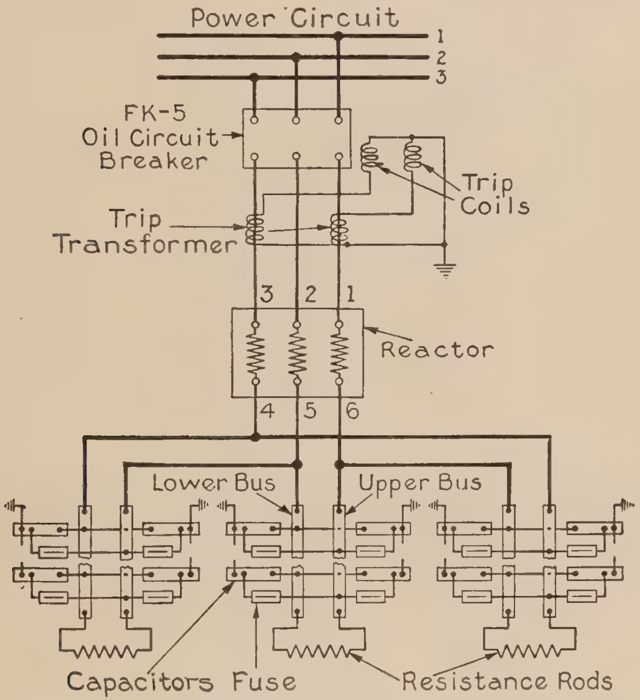

Fig. 78.—Connections for three-phase, 2,300-volt capacitor with reactors.

No attendant is required to operate a capacitor. To place it in operation, the control switch is closed, and to remove it from service, the switch is tripped open. It may be left on the line indefinitely with only a systematic inspection to see that it is operating satisfactorily. Because of this, the equipment may be installed in any out-of-the-way space or in a substation that may be inspected monthly only, or at even longer intervals. The operation is practically noiseless.

Since there are no revolving parts, no special foundation is necessary on which to locate the capacitor other than that necessary to bear its dead weight. The floor space required is small per kilovolt-ampere of capacitor capacity.

When operating at normal capacity continuously, the capacitor sections will have a temperature rise not to exceed 10°C.

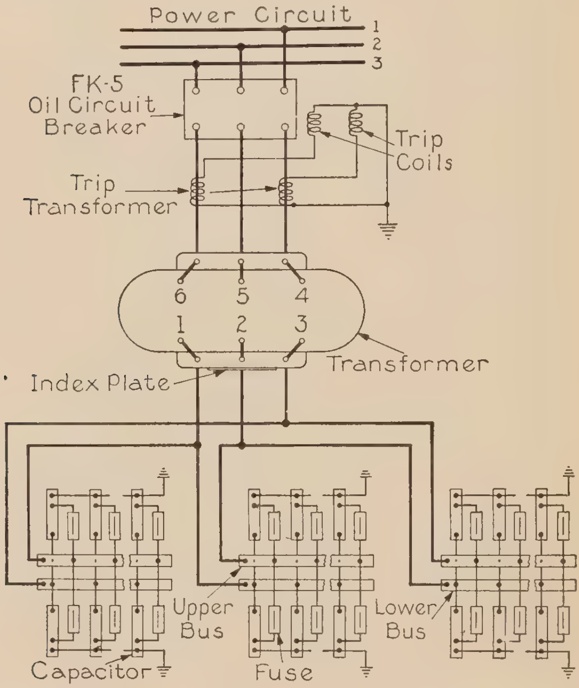

Fig. 79.—Connections for three-phase, 220-, 440-, or 550-volt capacitors with transformers.

The temperature rise of the reactance coils or the transformers will not exceed 55°C. The capacity of a capacitor is a function of the voltage and frequency, and it is, therefore, impossible to overload capacitor equipments as long as normal voltage and frequency are maintained.

In order to allow for voltage fluctuations found in practice, the equipments are designed to operate satisfactorily at voltages varying 10 per cent either side of the rated voltage of the equipment. It should be appreciated, however, that the corrective capacity of the equipment will vary in accordance with the square of the applied voltage.

81. Direct Installation on Low-voltage Circuits.—A line of low-voltage capacitors for direct connection on 220-, 440-, and 550-volt, 60-cycle circuits has been developed and is available for installations requiring power-factor correction in small capacities. With this extension to the present standard line for group correction, a complete line of power-factor-corrective equipment is available.

While there is a certain definite field for low-voltage capacitors, it must not be inferred that this method of correction should be recommended for all applications on low-voltage circuits. It is well known that the most advantageous point to apply power-factor-corrective apparatus is at the source of the low power-factor load. This point is generally on low-voltage circuits (220, 440, or 550 volts), but the higher cost for the low-voltage capacitors cannot always be justified as compared with the group method. Based on first cost only, the limit at present for 220-volt application is approximately 5 kva., and for 440-volt, approximately 30 kva. Some of the advantages of low-voltage capacitors are as follows:

1. Losses in the capacitors are less than one-half of 1 per cent.
2. Correction is applied directly at the source of low power factor and thus reduces the line losses caused by the reactive current over the entire system.
3. Voltage regulation of the circuit and starting characteristics of the motor are improved.
4. Underwriters' requirements are met without special provisions, such as transformer houses or vaults.
5. Installations are very flexible, facilitating additions to take care of increased load at low power factor.
6. Units are assembled for one-, two-, or three-phase connection.

Low-voltage capacitors follow the same general design as the high-voltage sections for group correction, using high-grade paper and specially treated insulating oils. These units are furnished with a small sheet-metal housing over the bushings with conduit entrance to comply in every way with the underwriters' requirements.

For 220-volt circuits, units have been standardized in ½- and 1-kva. capacity, one, two, or three phases, 60 cycles. By multiplying these two sizes, any capacity may be obtained by ½- or 1-kva. steps. For capacities above 5 kva. up to and including 30 kva., it becomes more economical from the standpoint of first cost to supply small group equipments consisting of type M transformers and standard 1,200-volt, 5-kva. sections, housed in a perforated sheet-steel box.

For 440-volt circuits, units have been standardized in 1 and 2 kva., one,- two,- or three-phase, 60 cycle. These units may be used in multiples for any capacity and, up to 60 kva., are comparable in price with group-corrective equipments and have the advantage of higher efficiency, as no transformers are used.

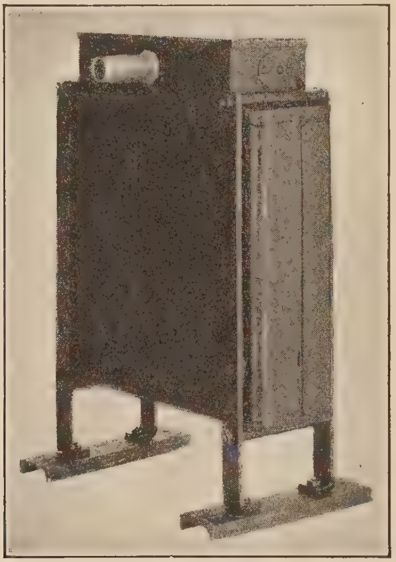

Fig. 80.—Single-unit capacitor for low-voltage circuits.

Broadly speaking, capacitors can be applied to advantage wherever conditions are such that an improvement of power factor is desired.

Each individual case, however, should be given careful consideration, inasmuch as there may be other means of improving power factor which will prove more advantageous. In new plants, or extensions to existing plants, for example, it may be found that synchronous motors can be applied more economically, and where very large capacities are involved, synchronous condensers can often be applied more economically.

The most favorable applications for capacitors in the industries are:

1. In existing plants where power-factor improvement is desirable. In such plants, it is desirable to bring about the improvement with the least possible disturbance to existing operating conditions. Replacement of induction motors by synchronous motors may disturb production and may involve the scrapping of perfectly good motors, which might prove to be a more expensive process than the addition of capacitors. Furthermore, the operators of the plant have been accustomed to operating the plant as it exists, and the addition of capacitors

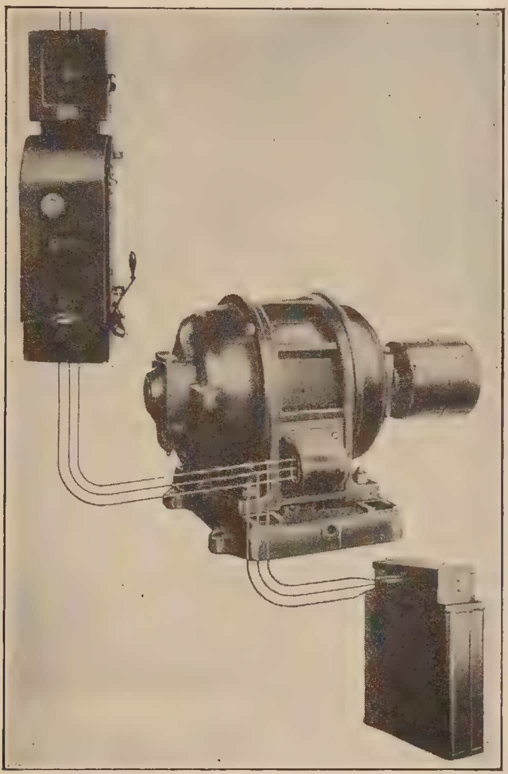

FIG. 81.—Capacitor connected to individual motor for power-factor improvement.

will not interfere with this in any way. No changes in foundations or other construction expenses will be involved, as the capacitors can be installed in convenient locations and can be distributed to suit the conditions, either in one main group on the bus or in smaller groups at advantageous locations or even at the terminals of the motors themselves.

2. In new plants or extensions, where the applications are such that the synchronous motors cannot be used to advantage and where the load conditions are such that the desired power factor cannot be obtained by the proper use of induction motors. The trend is toward the use of individual drive which offers many advantages in production, shop arrangement, and efficiency, all of which overbalance the saving in first cost of using larger motors for group drive, and in industrial plants, the capacitor will be found to be the most efficient means of improving the power factor from the standpoint of both energy consumption and production.

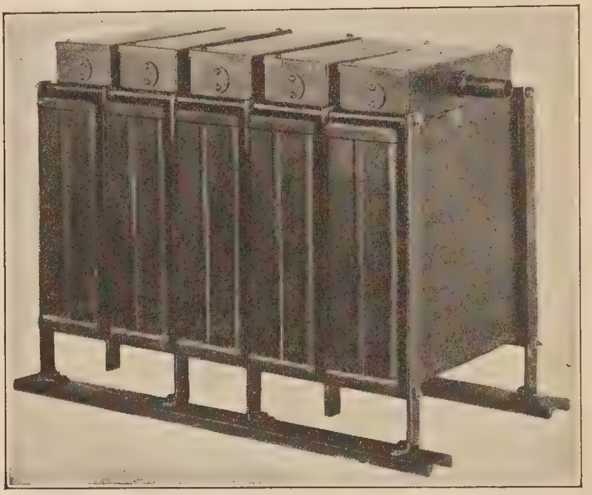
FIG. 82.—Group assembly of low-voltage capacitor units.

3. On individual motors at outlying points, where induction motors are most favorable from the simplicity and operating standpoint and where it is desirable to have high power factor.

For any of these applications, capacitors may be connected in small units directly to the motor terminals or may be combined in a bank and connected to a feeder to raise the power factor on a group of induction motors.

82. Control Required.—Where capacitors are applied to individual motors, no additional switches or protective devices are required, for, with the capacitor connected directly to the motor terminals (that is, inside the motor switch and protective device), it is protected by the motor-control device and discharges through the motor winding as soon as the motor line is opened.

Where a number of low-voltage capacitors are assembled as a unit to raise the power factor of a group of low-voltage motors, the capacitor (30 to 300 kva.) is connected to the line through an oil circuit breaker, which protects the unit against overload and permits disconnecting it if desired. Discharge resistances are supplied to discharge the condenser.

Where space factor and price advantage make the use of a combination of transformer and high-voltage capacitors more economical than low-voltage capacitors for improving the power factor of a group of low-voltage motors, an oil circuit breaker is necessary to disconnect the transformer and capacitors from the line. No discharge resistance is required, as the capacitors discharge through the transformer windings.

Capacitor equipments for 2,300-volt service consist of a number of units, a reactor for damping out the higher harmonics in the voltage wave, a discharge resistance for draining the condenser charge when disconnected from the line, and an oil circuit breaker for the control of the equipment.

83. Application.—Capacitors of the group type are usually installed either by a central station direct, or by an industrial having its own plant or purchasing power from a central station. In the latter case, the installation is usually justified by differential rates offered by the central station for improved power factor.

Figures 83, 84, and 85 show part of an installation of 4,800 kva. installed by the United Illuminating Company at Bridgeport, Conn. In the substation shown, there is installed a total of 2,400 kva. consisting of eight 300-kva., 2,300 volt, 60-cycle, three-phase equipments. The remaining 2,400 kva. are installed in a similar substation at a central point on this company's system.

The result of this installation has been to increase system power factor from approximately 65 to 90 per cent, with a resulting increase in generator capacity and in capacity of the cable running to the substations. The decrease in idle current in

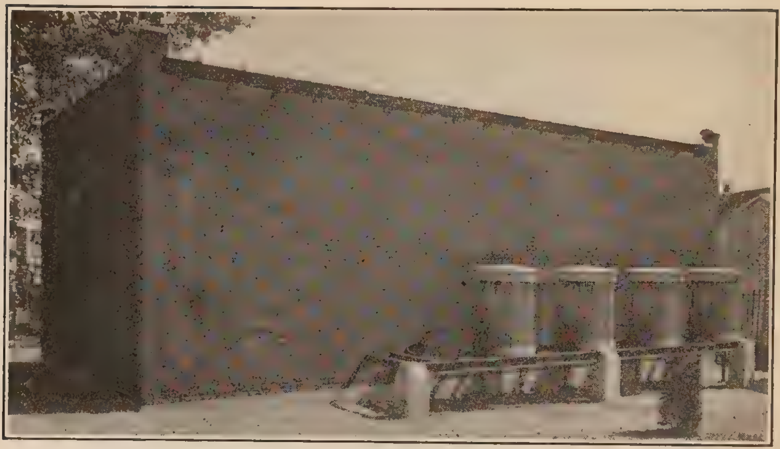

Fig. 83.—Exterior of capacitor substation, United Illuminating Co., Bridgeport, Conn.

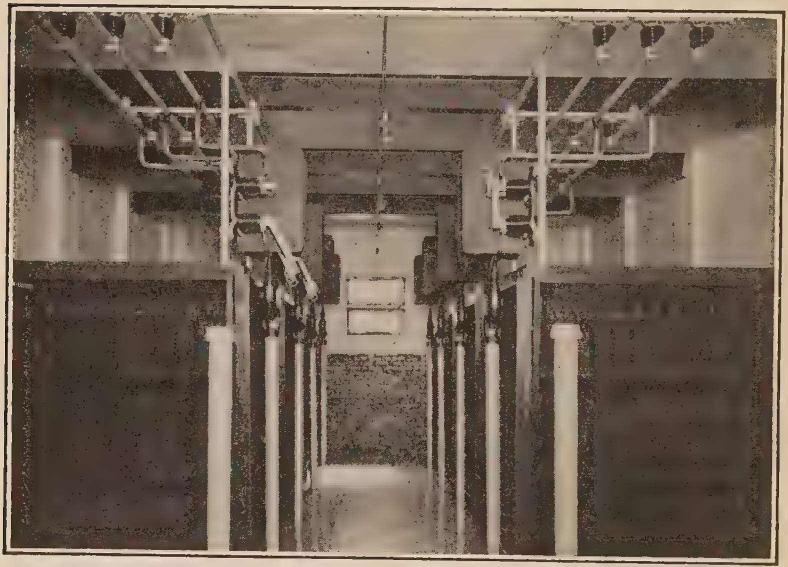

Fig. 84.—Interior of substation shown in Fig. 83 showing capacitor equipments.

the cables has resulted in greatly improved voltage regulation.

Careful analysis of this company's power-factor situation from both an engineering and financial standpoint led to the adoption of capacitors for this installation. Unusually low losses of capacitors, especially when figured for this company's operating conditions, make the installation particularly attractive in point of annual cost of the corrective apparatus. The capacitors being installed in unattended substations still further reduce the operating cost of the corrective equipment.

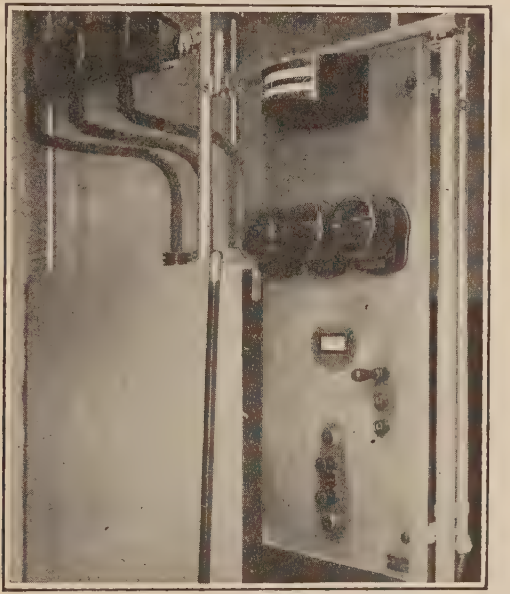

Fig. 85.—Control panel for controlling United Illuminating Company's capacitor equipments.

Figure 86 shows the location of 1,140 kva. in capacitors on the lines of the Rockville-Willimantic Lighting Company, Willimantic, Conn. This installation improved power factor from 65 to 85 per cent, resulting in a saving of over $15,000 the first year or approximately 84 per cent of the initial investment. The Willimantic Company purchases its power on a contract subject to a differential in rates for low power factor.

In order to improve the power factor of its system and take advantage of lower rates offered by the central stations, the Reo Motor Car Company of Lansing, Mich., has installed three

300-kva., 440-volt, 60-cycle, three-phase capacitors and one 1,000-kva., 4,000-volt, 60-cycle, three-phase synchronous condenser. The synchronous machine, having much higher losses than the capacitors, is operated only during the peak load, or a total of 55 hours a week, whereas the capacitors are operated 24 hours a day.

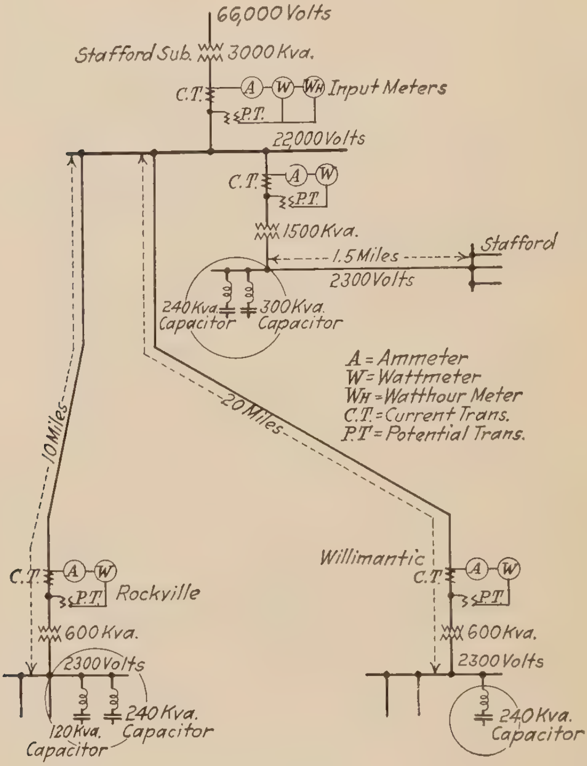

FIG. 86.—Location of capacitor installations on the Rockville-Willimantic Lighting Co., Willimantic, Conn.

This installation has resulted in increasing the power factor from approximately 65 to 88 per cent with a consequent reduction in the Reo Motor Car Company's bills of about $2,000 a month, which will pay the cost of the corrective equipment in about 15 months. On the other hand, the central station has profited by increased generator and line capacity more than sufficient to offset the loss in revenue due to the lower rate to the customer.

CHAPTER XV

POWER-FACTOR CORRECTION WITH FYNN-WEICHSEL MOTORS

The most recent important contribution to the problem of power-factor correction is the Fynn-Weichsel motor. This motor is a general-utility motor that combines the operating characteristics of two well-known types: the synchronous motor and the slip-ring induction motor using the slip-ring characteristics for starting and for carrying excessive overloads, and the synchronous characteristics for normal running. The present chapter was written especially for this volume by E. W. Goldschmidt.[1]

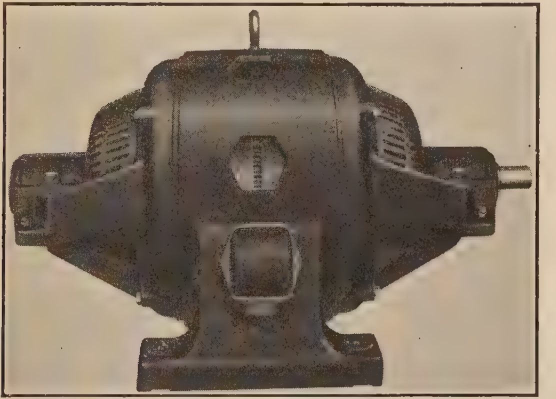

Fig. 87.—100-hp., eight-pole, 60-cycle, three-phase Fynn- Weichsel motor.

84. Construction of Motor.[2]—A 100-hp., eight-pole, 60-cycle, three-phase Fynn-Weichsel motor is shown in Fig. 87; its stator in Fig. 88 and its rotor in Fig. 89.

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[1] Eastern Executive Representative, Wagner Electric Corporation.

[2] For a more complete description of this motor, see paper entitled "A New Alternating-current General-purpose Motor," by H. Weichsel, presented at the Midwinter Convention of the American Institute of Electrical Engineers, Feb. 9–12, 1925; also paper entitled "The Motor That Corrects Power Factor," by H. Weichsel, read at a meeting of the Associa-

The rotor is provided with slip rings and a commutator. In the larger units, these are arranged on opposite ends of the rotor; and in the smaller units, both are located on the same end. The rotor slots carry two windings, one on top of the other. In the bottom of the slots is a small direct-current winding which is connected to the commutator; and in the top of the same slots is a standard polyphase winding which is connected to the slip rings.

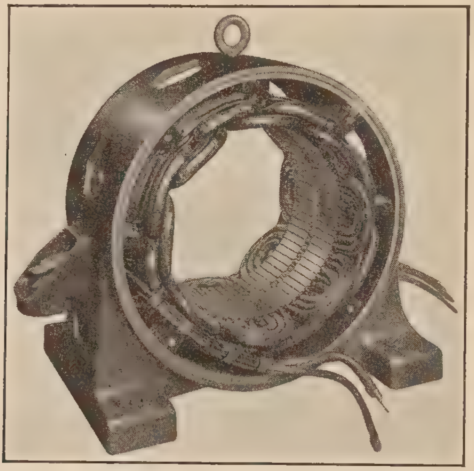

Fig. 88.—Stator of 100-hp., eight-pole, 60-cycle, three-phase Fynn-Weichsel motor.

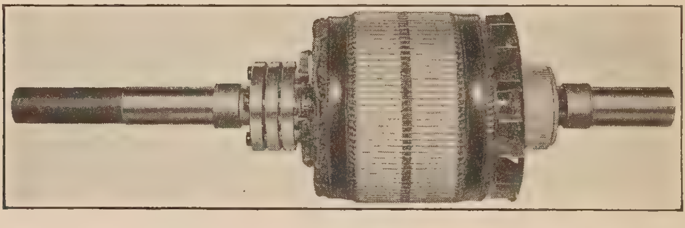

Fig. 89.—Rotor of 100-hp., eight-pole, 60-cycle, three-phase Fynn-Weichsel motor.

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tion of Iron and Steel Electrical Engineers, at Pittsburgh, Pa., Feb. 16, 1924, and reprinted in the *Iron and Steel Engineer*, April, 1924. Both of these papers have been reprinted in pamphlet form by the Wagner Electric Corporation, St. Louis, Mo.

The stator has no well-defined polar projections, being similar in appearance to the stator of a standard induction motor. Two concentrically wound windings of the simplest kind possible are carried in the stator slots. One is the main direct-current field winding *F*, and the other an auxiliary winding *A*; the two being displaced 90 electrical degrees from each other.

The normal running connection between the individual windings is diagramatically given in Fig. 90. It will be noted that the field winding *F*, located on the stator, is connected in series with the brushes on each side of the commutator, and that the axis of the brushes forms an angle less than 90 deg. with the axis of the field winding *F*. The auxiliary winding *A*, also located on the stator, is short-circuited. The slip rings are connected to the line.

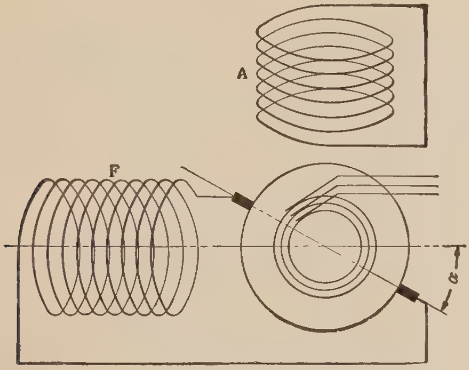

Fig. 90.—Running connections of Fynn-Weichsel motors.

In starting, resistance is inserted in the circuits of the stator windings *F* and *A*, Fig. 91*a*, giving the same starting performance as that inherent to a slip-ring induction motor. To avoid switching during the starting period, the commutated rotor winding in small- and medium-sized motors is kept permanently in series with the main field winding *F* and its resistance as shown in Fig. 91*c*. Generally speaking, this arrangement influences favorably the starting-torque characteristics for a given resistance in the main field circuit. The only operations necessary in starting are the closing of the line switch and the moving of the starter handle from "off" to "running" position.

Below synchronous speed, both secondary (stator) windings carry an alternating current, the frequency of which is proportional to the slip. In addition to the e.m.f. induced in secondary circuits by the revolving magnetic field, there is an additional e.m.f. in the circuit including the direct-current field winding *F*. This e.m.f. is due to the cutting of the revolving magnetic field by the direct-current winding on the rotor. This superimposed e.m.f. in the direct-current field winding varies approximately as a sine function of the time. The effect of the direct-current armature winding in the field circuit during the starting period is to add a pulsating torque to the uniform torque normally exerted by an induction motor.

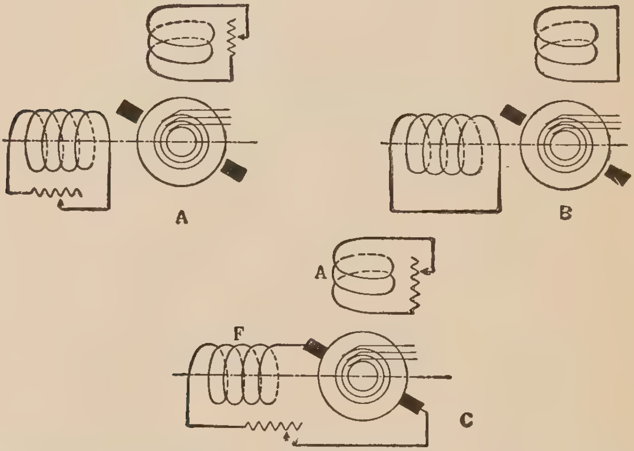

Fig. 91.—Starting connections of Fynn-Weichsel motors. Illustration A shows the initial connections for large-size motors; B the same connections with resistance cut out of circuit prior to switching to running connections shown in Fig. 90. Illustration C shows the starting connections used for small- and medium-sized motors. With these conditions, no switching is necessary.

When the motor is up to speed, the auxiliary winding *A* is short-circuited and carries no current, for since the motor is operating at synchronous speed, this winding cuts no lines of force. The main field winding, on the other hand, is supplied with direct current from the commutated rotor circuit.

The voltage between commutator segments and between brushes in all ratings is relatively small as compared with an ordinary direct-current motor. As a result, commutation of the rotor current is accomplished without sparking. Should the direct-current brushes wear out and there be none on hand to replace them, an unlikely occurrence, the terminals of the direct-current field winding *F* can be connected together, in which case the motor corresponds to an ordinary slip-ring induction motor.

The motors are arranged for clockwise rotation. Reversal of direction of rotation is accomplished by interchanging the connections of any two wires to the slip rings, and by moving the rocker arm from a position marked "right hand" to a position marked "left hand."

The starting equipment, a single unit, consists of two starting resistors, one for each of the stator circuits. The starter may be provided with low-voltage release and with overload protection. If desired, remote controlled automatic starters may be used.

85. Performance of Motor. *Starting Characteristics.*—The starting characteristics of a typical Fynn-Weichsel motor are

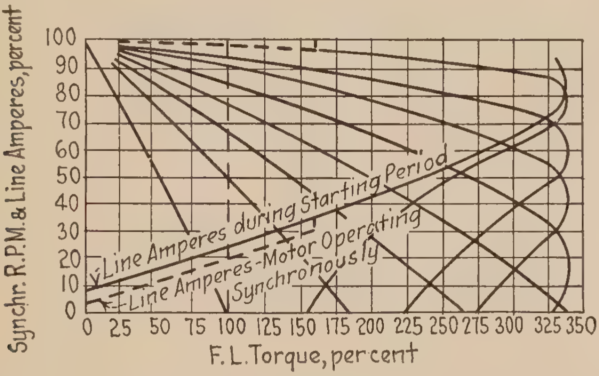

FIG. 92.—Typical speed-torque characteristics of Fynn-Weichsel motor, when in starting connection.

shown in Fig. 92. They are similar to those of a slip-ring induction motor with the exception, however, that a slip-ring motor attains a maximum speed of 95 or 96 per cent of synchronous speed while the Fynn-Weichsel motor attains synchronous speed. A starting torque of 150 per cent of full-load torque can be obtained with a starting current of 150 to 200 per cent of full-load current. The motor is so designed that it will accelerate a load as great as 150 per cent of full load from rest to synchronous speed without change in operating connections until synchronous speed is attained.

While the starting torque of this motor, up to the point of pull-in, is the same as that of a well-designed slip-ring induction motor, the torque during the interval of change from induction to synchronous speed is in excess of full-load torque. This characteristic is in marked contrast to the common synchronous motor, the pull-in torque of which is but a fraction of the full-load torque.

Running Characteristics.—As a synchronous motor, the Fynn-Weichsel will carry 150 per cent of full load without falling out of step. At higher loads, as shown in Fig. 93, it drops into induction-motor characteristics, and continues to run as a slip-ring induction motor to the breakdown point of approximately 300 per cent full load before it stops. The value of this characteristic cannot be too strongly emphasized, as it enables the motor to carry temporary excess overloads in the same way as a squirrel-cage or slip-ring induction motor, thereby making the motor just as suitable and practical in its operation as present kinds of induction motors. The motor has still the further peculiarity that when the overload is removed it will automatically resume synchronous speed.

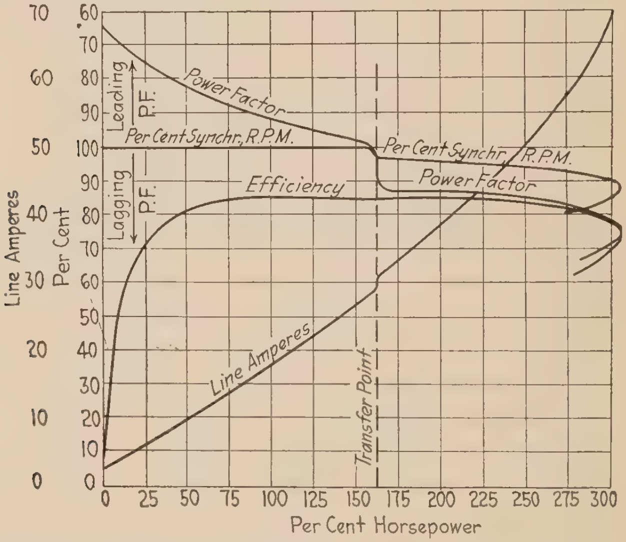

FIG. 93.—Load characteristics of the Fynn-Weichsel motor adjusted to operate in parallel with induction motors. These curves apply to a 15-hp., 440-volt, 1,800-r. p. m., 60-cycle three-phase motor.

Power-factor Characteristics.—The Fynn-Weichsel motor is available for a wide range of characteristics, particularly in respect to power factor at various loads. Figure 93 shows the characteristics of a motor designed to operate in parallel with induction motors for correction of low power factor. It will be noticed with this particular motor that its power factor at no load is 65 per cent leading, at one-half load 80 per cent leading, at full load 92 per cent leading, and at one and one-half load, unity. At this point, the motor drops out of synchronism and operates as an induction motor with a lagging power factor.

In Fig. 94 the effect of this motor upon a circuit when operated in parallel with a slip-ring induction motor of the same size is shown. The lower of the two power-factor curves is that of two slip-ring motors in parallel, the upper that of a combination of one slip-ring and one Fynn-Weichsel motor. Similarly, of the two curves of line current, the lower end shows the current drawn by one Fynn-Weichsel and one slip-ring motor in parallel, while the upper curve shows the current drawn by two slip-ring motors in parallel.

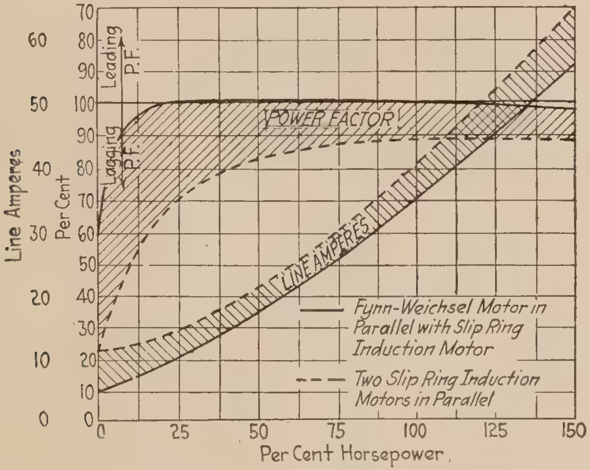

FIG. 94.—Comparison of power factor and line current when using two slip-ring induction motors and when using one slip-ring induction motor with one Fynn-Weichsel motor.

Summary of Advantages.—Summarizing, the Fynn-Weichsel motor, in addition to being a power-factor corrective, is eminently well adapted to applications requiring heavy starting torque, operates at synchronous speed under normal load conditions and will stand heavy overloads and widely fluctuating loads without breakdown. It requires no direct-current supply for field excitation and the control equipment is as simple as that used for an ordinary slip-ring induction motor. It thus combines all the favorable and desirable characteristics of both the slip-ring induction motor and the synchronous motor, and yet possesses none of their objectionable features.

86. Application of Motor.—A squirrel-cage induction motor, because of its extraordinary mechanical simplicity and reliability, will, in spite of its poor power-factor performance, continue to be the backbone of electric power. Consequently, the Fynn-Weichsel motor has been designed to team-up with induction motors, supplying magnetizing current for such motors in addition to doing its quota of the work.

Because of the team idea, the Fynn-Weichsel becomes an integral part of the whole installation, and to get best results should be installed only after a thorough canvass of the complete motor set-up.

Induction motors should, as far as possible, be placed on applications where they can operate near their full load with moderate starting duty and high speed. This will better a plant's power factor and reduce the amount of magnetizing current to be supplied by Fynn-Weichsel motors or from other sources.

Fynn-Weichsel motors should be used where constant speed is important, where starting duty is heavy, and on service where induction motors would operate at poor power factor. In the latter case, the Fynn-Weichsel motor takes that part of the load that is at the poorest power factor and eliminates it entirely from the quota of corrective kilovolt-amperes to be supplied. All the corrective kilovolt-amperes of the Fynn-Weichsel are thus available for supplying magnetizing current to other motors.

From the foregoing, it is evident that a fundamental advantage of motor correctives over all kinds of pure correctives is that the corrective motor carries its quota of the load, and thus by its own working reduces proportionately the amount of corrective kilovolt-amperes required. On a 100 per cent correction, this will at least cut the corrective kilovolt-amperes required in half.

For example, let us assume two 100-hp. motors. If both are induction motors and their average magnetizing power is 44.5 kva. each, it will require 89.0 kva. of corrective power to be supplied by condensers or other source to bring the power factor to unity. On the other hand, if one of these motors is replaced by a Fynn-Weichsel, the latter has to supply only 44.5 kva. to bring the power factor to unity. Thus the first cost of the kilovolt-ampere corrective for a given price per kilovolt-ampere is cut in half by use of the Fynn-Weichsel motors.

In order to give some idea of the approximate cost of correction with Fynn-Weichsel motors, five examples of motors in pairs are worked out in Figs. 94 to 98 inclusive. Four of these are squirrel-cage motors ranging in speed from 720 to 1,800 r.p.m. The fifth one is a slip-ring motor operating at 900 r.p.m. The total corrective kilovolt-amperes are taken as the sum of the lagging current of the induction motor and the leading current of the Fynn-Weichsel motor. The reason for this is that the Fynn-Weichsel displaces a similar induction motor in addition to supplying its leading current to compensate for lagging current taken by other motors on the line.

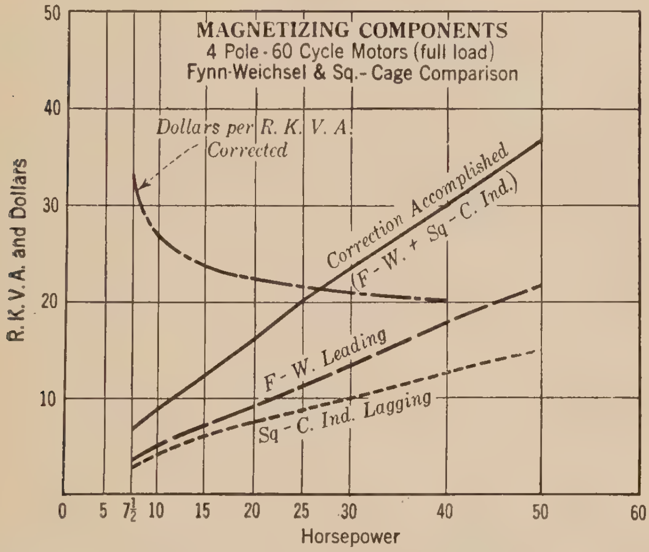

FIG. 95.—Reactive kilovolt-ampere correction accomplished and approximate cost per corrected reactive kilovolt-ampere where 1,800-r. p. m. Fynn-Weichsel motor replaces 1,800-r. p. m. squirrel-cage motor.

Examination of these curves, particularly the cost in dollars per reactive kilovolt-ampere corrected by Fynn-Weichsel motors, shows that the advantages of correction are greatest with the slowest-speed motors. In other words, the cost of correction decreases with the speed of the motor corrected.

These examples are not the most favorable to the Fynn-Weichsel motor because in an actual installation where a large number of motors are involved, it is usually possible to replace with Fynn-Weichsels the motors causing the most trouble, in this way moving beyond the need of correction more than half of the kilovolt-amperes required for power-factor correction.

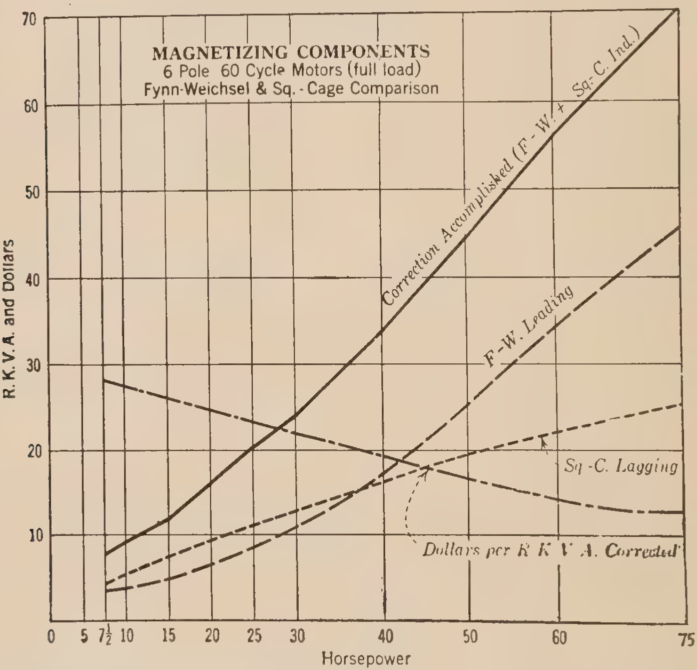

FIG. 96.—Reactive kilovolt-ampere correction accomplished and approximate cost per corrected reactive kilovolt-ampere where 1,200-r. p. m. Fynn-Weichsel motor replaces 1,200-r. p. m. squirrel-cage motor.

Range of Economic Application.—The economic field of application of the Fynn-Weichsel motor, like that of all other power-factor correctives, is naturally governed by the particular conditions existing in each individual case. These conditions determine the relative costs and advantages of correction by the various means available. It should always be remembered, however, that when a Fynn-Weichsel motor is installed, some correction is always obtained and an approximately equal amount of reactive kilovolt-amperes kept off the system.

In general, it may be said that the economic field of application of the Fynn-Weichsel motor as compared with static condensers occupies a middle position.

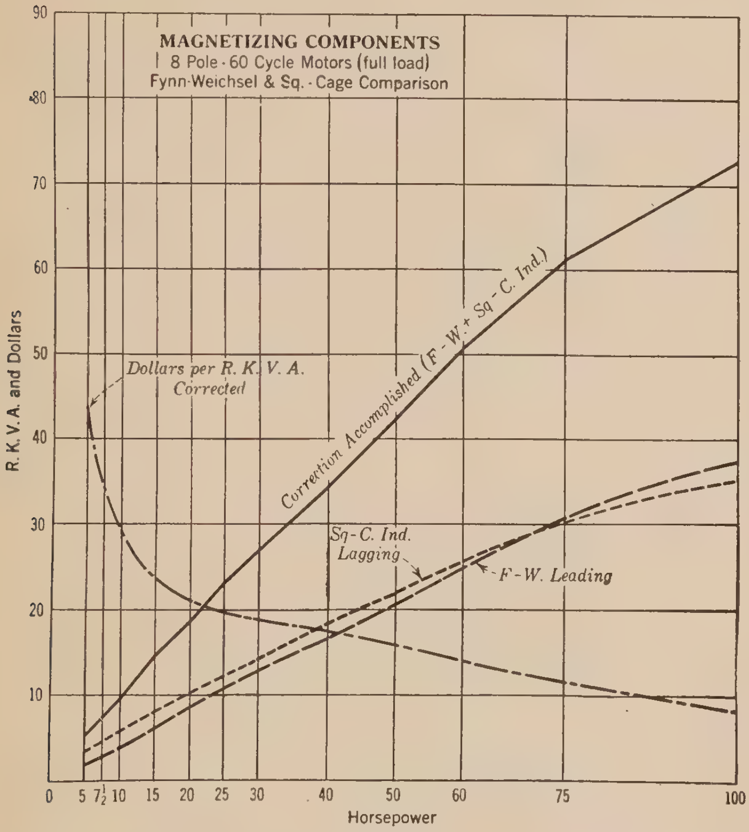

FIG. 97.—Reactive kilovolt-ampere correction accomplished and approximate cost per corrected reactive kilovolt-ampere where 900-r. p. m. Fynn-Weichsel motor replaces 900-r. p. m. squirrel-cage motor.

On the one extreme, the Fynn-Weichsel motor is not the most economical way of correcting power factor when it must be used in very small sizes to pair-up with small induction motors. For this reason, the use of Fynn-Weichsel motors in very small sizes is not recommended. On the other hand, a number of small motors in a department can be corrected as a group by one or more large

Fynn-Weichsel motors in the same locality more economically, everything considered, than by connecting condensers across the terminals of each individual small motor.

Considering the other extreme, Fynn-Weichsel motors are not the most economical way of effecting *bulk* correction for a large total motor load. But bulk correction at transformer terminals does not benefit the power user as far as line losses upon his own premises are concerned. These losses with a large motor load are likely to be great in amount and the voltage regulation poor. It is better, therefore, for the correction to be made close to the motor terminals. This can be accomplished by pairing Fynn-

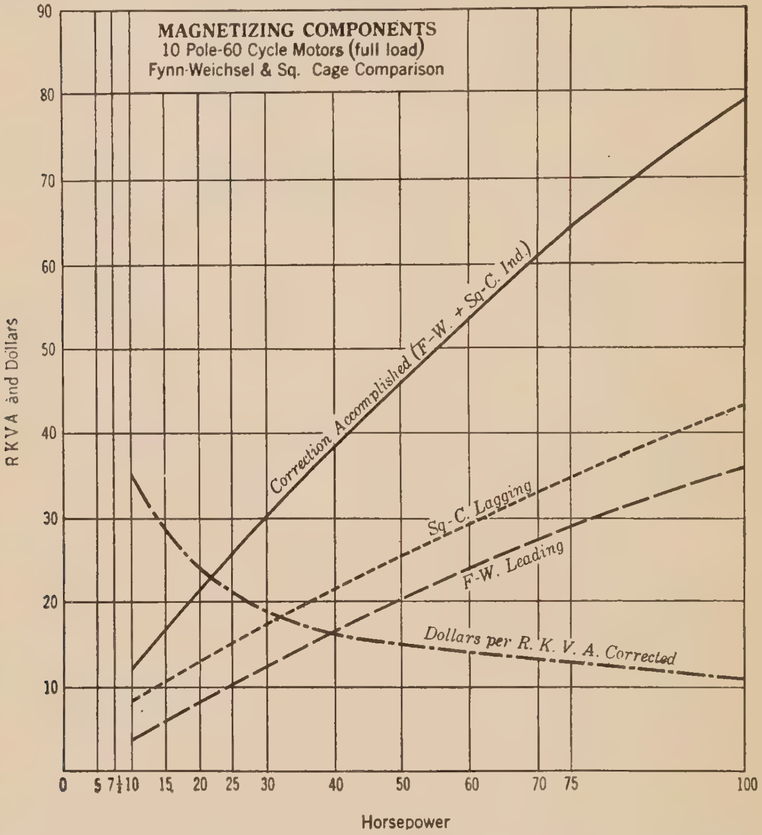

FIG. 98.—Reactive kilovolt-ampere correction accomplished and approximate cost per corrected reactive kilovolt-ampere where 720-r. p. m. Fynn-Weichsel motor replaces 720-r. p. m. squirrel-cage motor.

Weichsel motors with individual motors or with groups of motors.

87. Typical Examples of Benefits Derived through Correction of Power Factor by Means of Fynn-Weichsel Motors.—The McClymont Marble Company, Milwaukee, Wis., added 145 hp.

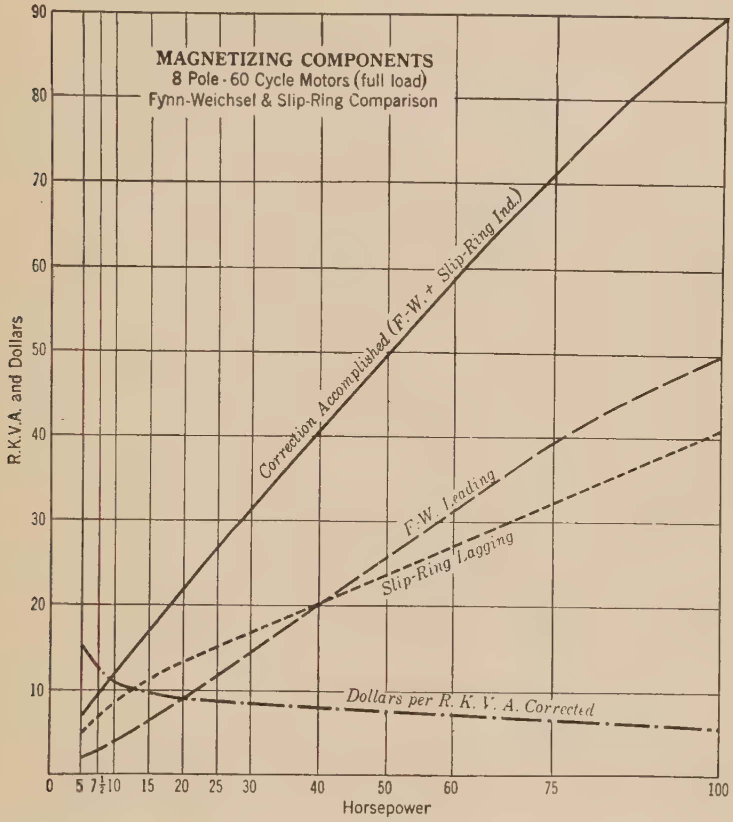

FIG. 99.—Reactive-kilovolt-ampere correction accomplished and approximate cost per corrected reactive kilovolt-ampere where 900-r. p. m. Fynn-Weichsel motor replaces 900-r. p. m. slip-ring induction motor.

in Fynn-Weichsel motors to an existing load of 550 hp. in squirrel-cage induction motors. With the squirrel-cage motors alone, the average monthly power factor was about 61 per cent. During the month ended Nov. 11, 1924, when 145 hp. in Fynn-Weichsel motors were operated in addition to the squirrel-cage motors, the average power factor was 71.6 per cent, or a gain of

10.6 points, despite the fact that the power company changed its meters from the secondary to the primary side of the service transformers as soon as Fynn-Weichsel motors were installed. The improvement in power factor reduced the customer's demand for the month by $43. Since the period to which the preceding remarks apply, two additional Fynn-Weichsel motors have been installed, totaling 25 hp. All the Fynn-Weichsel motors are three phase, 220 volts, and are listed below:

Number	Horsepower	Application
1	7.5	Four longitudinal carborundum cutters
1	30	One transverse carborundum cutter
1	25	Air compressor
1	15	Two gang saws
2	7.5	Rubbing beds
1	10	Sand pump

An interesting comparison can be drawn in the case of the rubbing beds, each of which weighs 18,000 lb. Two as stated above are equipped with 7.5 hp. Fynn-Weichsel motors; the others with 10- and 15-hp. squirrel-cage induction motors. These machines require about 6 hp. to keep them running and about three times this power to start. Obviously, a 7.5-hp. motor carrying a 6-hp. load is operating under much better conditions, not only of power factor but of energy efficiency, than a 10- or 15-hp. motor on the same load.

It will be noticed that one Fynn-Weichsel motor is used to drive two gang saws, as opposed to two gang saws operated separately by one 10- and one 15-hp. squirrel-cage induction motor, respectively. All of these saws require about two and one half times the power to start that they use when running.

The 25-hp. Fynn-Weichsel motor belted to an air compressor operates satisfactorily despite the fact that, according to the manufacturer's recommendations, it requires 31 hp.[1]

Elizabeth Sash, Door, and Supply Company, Elizabeth, N. J.—Before the Fynn-Weichsel motor was even considered, this firm had a total connected load of 175 hp. in induction motors, 156 hp. of which were in the shop. Owing to additional power needs, it was proposed to add three 7½-hp. motors and one 25-hp. motor. Tests showed that the average demand was only 10 kw. with a minimum of 5 kw. and a maximum of 20 kw. The power factor was about 58 per cent. The kilovolt-ampere demand ranged between 9 and 35.

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[1] PERRY, A. M., and ANDERSON, H. C., "Benefits of Power-factor Correction," *Elec. World*, Feb. 14, 1925.

The new 25-hp. motor contemplated was to drive an exhaust fan. It was estimated that this would require an average total load of 45 kva. in the mill and the installation of larger transformers. The city electrical inspector would not allow the 25-hp. motor to be connected to the mill circuit, as the wires were quite warm with the load they were already carrying. To put in larger feeders and to install the vault required for the larger transformers would have cost $1,800, and the plant would have to be shut down while these changes were being made. It was suggested that if the power factor on the mill circuit were improved to 90 per cent or better, the necessity of making these costly changes might be avoided.

It was decided to install a 25-hp. Fynn-Weichsel motor to drive the exhaust fan instead of the induction motor first contemplated. This type of motor was selected in preference to an ordinary synchronous motor because of its better starting characteristics and its ability to carry heavy overloads resulting from voltage dips.

After the installation of the Fynn-Weichsel motor, the kilowatt demand averaged 27 kw. and the kilovolt-ampere demand 29 kva., while the average power factor was found to be over 90 per cent.

In addition to saving the cost of installing new transformers and wiring, the new motor apparently reduced the power bills below what they would have been had an induction motor taken its place by reducing the I^2R loss in the line on account of improved power factor.[1]

Ludlow-Saylor Wire Company, St. Louis, Mo.—G. Duncan, president of this company, reported to the Wagner Electric Corporation as follows in regard to a Fynn-Weichsel motor installed in the Ludlow-Saylor plant:

> It is very gratifying to us to be able to say that this motor has given us excellent results in every respect. We have not experienced a single

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[1] Perry, A. M., and Anderson, H. C., "Benefits of Power-factor Correction," *Elec. World*, Feb. 14, 1925.

interruption of service, nor expended any money for repairs. We have had superior performance of our wire looms because of the high starting torque, and the constant speed of the motor, which is an important factor with looms handling fine wire such as is used in fly-screen cloth. The writer feels that he is making a conservative statement in advising you that our output has increased fully 10 per cent, as a result of the constant speed, which eliminates breakage in fine wires.

Norwood Sash & Door Company, Cincinnati, Ohio.—This company had in operation a 440-volt, 60-cycle, three-phase generator rated at 542 amp. per terminal.

The load on this machine on Apr. 23, 1925, was 210 kw. at 450 volts, 420 amp., 328 kva., and 65 per cent power factor. In addition, power was purchased from the Union Gas and Electric Company to operate three disk fans for exhausting the shavings from the woodworking machinery. This energy was purchased because the generator would not successfully carry the additional load, on account of bad voltage regulation due to a bad power factor and also on account of actual overload on the generator in amperes.

The following motors were placed on the three disk fans, and when placed in operation, the actual load on these machines was found to be as given below:

Rating	Load
140 hp., 1,200-r.p.m. motor	19 kw.
130 hp., 1,200-r.p.m. motor	40 kw.
160 hp., 1,200-r.p.m. motor	52.5 kw.

Instead of purchased energy being used for these motors, they are now connected to the company's own generator, the load on which is now as follows:

450 volts, 500 amp., 321 kw.
390 kva., 82.5 per cent power factor.

Voltage regulation has been greatly improved and the company is saving about $500 monthly, formerly paid to the local central station for power to operate these fans.

George Whiting Paper Company, Menasha, Wis.—Total connected alternating-current motors in plant, 159 hp. Power factor before installation of Fynn-Weichsel motor, 55 per cent.

One 50-hp., three-phase, 60-cycle, 900-r.p.m. Fynn-Weichsel motor was installed on a calender stack, replacing a 50-hp.

induction motor. The power factor after the installation of the Fynn-Weichsel motor was 71.7 per cent.

The reduction in the demand charge due to operating with a power factor of 71.7 per cent instead of 55 equaled $47.25 per month or $567 per year. This is 53 per cent of the cost of the Fynn-Weichsel motor, making no allowance for the motor removed.

CHAPTER XVI

IMPROVING THE POWER FACTOR WITH THE ELECTRIC FURNACE

Attention has been called to the fact that the power factor of an induction motor can be increased simply by loading the motor in such cases where induction motors can be given suitable loads, as by motor substitution, thereby increasing the total current but increasing the working current and the kilowatt input more rapidly than the magnetizing current. The method herein described by L. V. Clark[1] operates in much the same way, only unity-power-factor heating loads are used to accomplish the purpose along with the regular applications of such heating loads. The uses and advantages of electric furnaces of the resistance type are also explained.

88. Introductory.—The use of electricity for supplying heat in many industrial processes has increased very rapidly in the past few years, but it is still in its infancy. These heating processes were, before the introduction of electric heat, always carried on with the various well-known fuels such as wood, coal, coke, and oil. Gradually, however, as the advantages of the newer form of heat are becoming more widely known, the more prevalent forms of fuel are being displaced.

It is the purpose of this chapter to point out briefly the field of industrial heating applications which have been or will be in the near future electrified, and to show the effect which this will have on the average industrial load. Inasmuch as we are concerned in this book only with the attainment of that power-factor ideal of 100 per cent, the electric furnace discussion will be entirely concentrated on the resistance-type furnace.

89. Reasons for the Adoption of the Electric Furnace.—Electricity for heating purposes was first used in appliances for the home such as flatirons, toasters, curling irons, and so forth, where the matter of convenience was of primary importance and the cost of fuel of heating medium of minor importance. The use of these appliances has grown and is still growing very fast. Consequently, inquiring minds in the industrial field began to wonder why they were not using electric heat in some of the manufacturing processes where the cost of fuel was also of minor importance. It will be noticed from the way the heating business developed that people had, of course, compared the cost of a given number of B.t.us. produced by electricity and the other forms of heat and discovered on this basis that electric heat was entirely too expensive to be used in competition with the then prevailing methods of generating heat. Consequently, as has just been stated, electricity was used only when the cost of the electric energy consumed was a minor item.

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[1] Industrial Power Engineer, Connecticut Light and Power Company.

The industrial plants found numerous places where electric heat worked out to their benefit and gradually they became acquainted with the advantages of this form of fuel. As their investigations led them into larger furnaces and higher temperatures, it became apparent that even on fuel cost alone electricity, in some cases, was not out of bounds and in many cases was less than the fuel cost of using other forms of fuel.

This did quite a bit to boost the further use of this newer form of heat, and as experience in various applications was gained, it was found that there were various savings made in the overall cost of a manufactured product which required heating operations which were of paramount importance. From these experiences the overall cost of the product is now always considered in studying a possible application for electric heat, and the comparison of fuel cost *versus* electricity cost is no longer the basis on which to justify or disprove the electric furnace.

The reasons why the electric furnace in many cases reduces the overall costs when it is used are as follows:

1. Control of the furnace chamber is absolutely automatic. No reliance is placed on the human element.

2. The atmosphere in the electric furnace is always the same, that is, slightly oxidizing, and does not vary from day to day depending on the atmospheric conditions or the operator.

3. The electric furnace may be placed in any part of the industrial plant where it can best fit into the line of production. This means a saving in labor and cartage costs, since in the case of fuel-fired furnaces it is a general practice to have all heat-treating operations carried on in a separate building.

4. The fact that working conditions are greatly improved around the electric furnace over other types is another big reason for their use. Practically no heat is radiated into the room to the discomfort of the workman, and there is no dilution or contamination of the atmosphere such as is the case with other furnaces.

90. Field for Electric Heat.—These may be generally classified as follows:

A. Low-temperature applications:

1. *Drying.*—Lacquers, paints, and so forth. Temperatures up to 250°C.

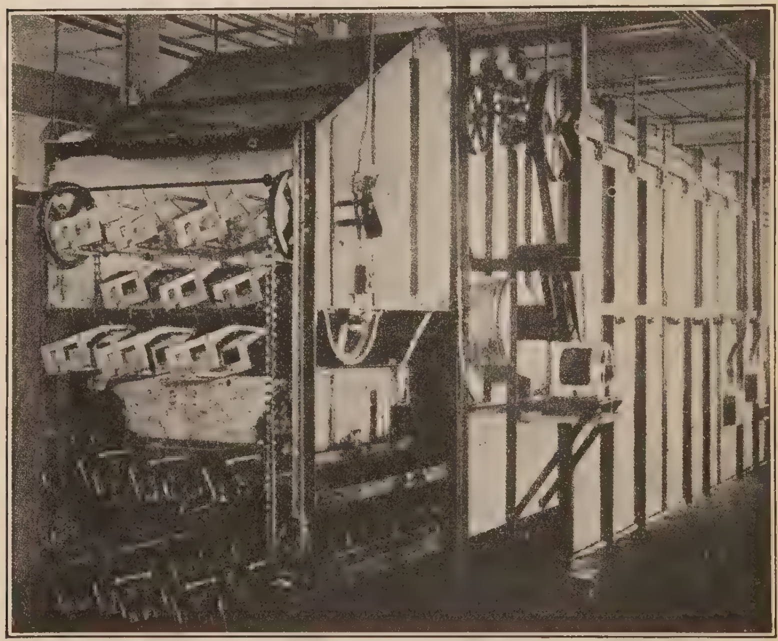

FIG. 100.—Baking enamel on typewriter parts. Oven size, 5½ . by 35 ft. by 10½ ft. high. Connected load, 112 kw. Operating temperature, 400°F.

2. *Japanning.*—Baking japan finish on metal parts. Temperature approximately 425°F.(Fig. 100).

3. *Core baking.*—Cores used for making castings in foundries. Temperature approximately 400°F.

4. *Drawing or tempering.*—Steel requiring a final temper is heated either in an air chamber or an oil bath to the proper temperature.

5. *Melting.*—Low-temperature metals only, such as lead, zinc, solder, type metal, and so forth. Examples are shown in Figs. 101 and 102. Range up to 700°F.

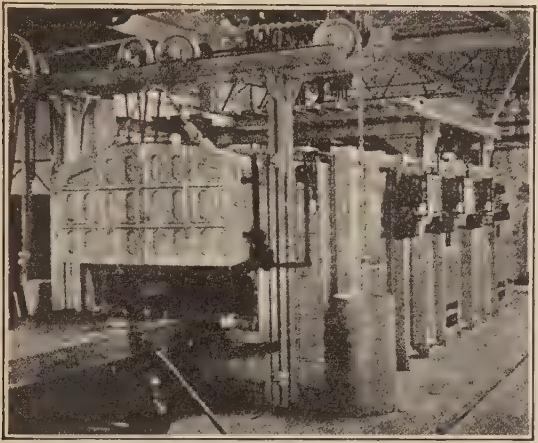

Fig. 101.—Annealing brass tubing. Furnace size, 54 in. by 16 ft. by 18 in. high. Connected load, 330 kw. Operating temperature, 1200–1350°F.

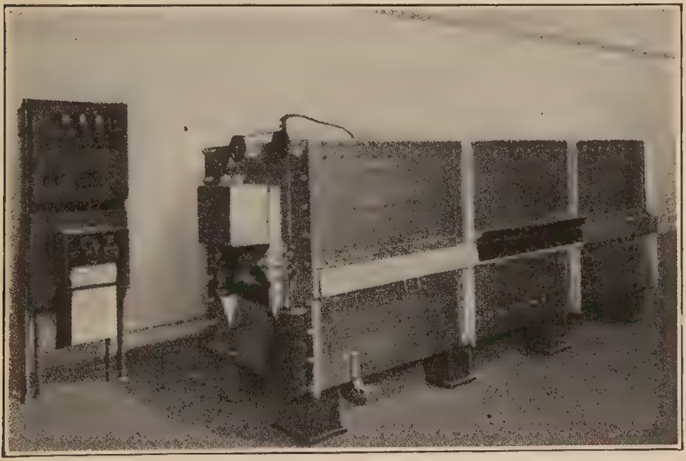

Fig. 102.—Automatic continuous electric roller hearth furnace, General Furnace Company.

B. Medium-temperature applications:

1. *Annealing.*—Brass, copper, aluminum, and so forth (Fig. 101).

C. High-temperature applications:

1. *Heat treatment of steel.*—Hardening, annealing, normalizing, carburizing. Range approximately 1400-1600°F.(Fig. 102).

2. *Heating of steel for forging.*—In general, the resistor-type furnace can take care of this operation only on steels that do not require more than 1850°F.

3. *Vitreous enameling.*—Range 1600-1700°F. An electric vitreous enameling furnace of the batch type having a connected load of 200 kw. is shown in Fig. 103.

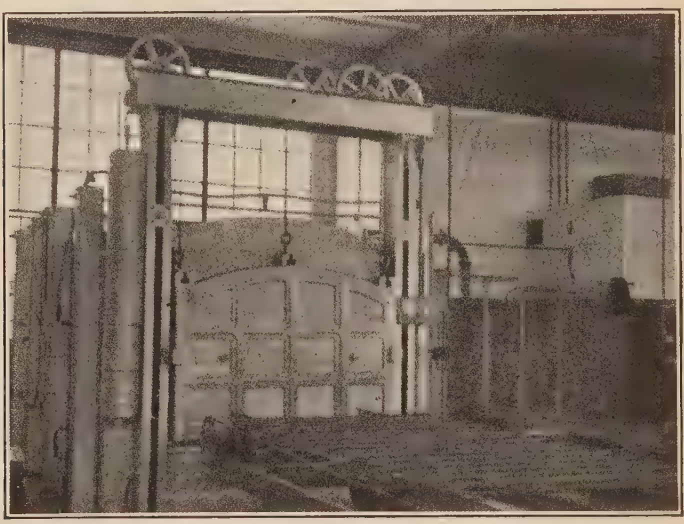

Fig. 103.—Electric vitreous enameling furnace (batch type). Connected load, 200 kw., General Furnace Company.

91. Summary.—The previous paragraphs of this chapter were given with an idea of picturing the enormous possibilities for the future use of electric heat. This is true, of course, particularly in the metal industries. The size of this heating load will, in some cases, greatly outdistance the motor load, and consequently any poor inherent power factor of the induction-motor load will, in some cases, be swamped with the 100 per cent power-factor heating load, so that the resulting plant power factor will be high. The writer has one actual case in mind of a factory having a 225-kw. motor load with an average power factor of 50 per cent and a heating load of 775 kw. at 100 per cent power factor, giving a resulting plant power factor of 94 per cent. This, perhaps, is an unusual case, but estimates show that the heating load of the future will in some cases be equal to the motor load and in many cases double the motor load.

By way of further illustration, if the power factor of a given motor load is 70 per cent, and an equal 100 per cent power-factor heating load is added, the overall power factor for the plant will be 89.2 per cent, and by doubling the heating load, the power factor will be increased to 94.6 per cent.

It can thus be seen that in many cases a very good power factor for a plant load can be obtained without the addition of special corrective equipment. It is the writer's firm conviction that the field in the future for power-factor-corrective equipment will be outside the metal industries entirely, as it will not be needed within that industry on account of the heating load.

The other forms of power-factor-corrective equipment discussed in this book all mean an investment on the part of the plant management for corrective equipment alone, and in some cases this equipment has small losses which are ever present. With the case of the electric furnace, it is doing useful work of its own and is not incurring any losses incident to power-factor correction, but at the same time it improves the power factor of the entire industrial load.

As is true in any engineering study, each case must be considered separately, and in a search for a way out of the power-factor dilemma, this is no less true. It has been the object of this brief chapter in this book to point one way out that is slowly but surely coming for some of the metal industries.

CHAPTER XVII

LOCATION OF POWER-FACTOR-CORRECTIVE APPARATUS

There are long transmission lines and short transmission lines, new systems with plenty of capacity and old systems with limited or inadequate capacity. There are short feeders and mains, and long feeders and mains in new and in old secondary and plant distribution systems. There are small induction motors, large induction motors, and induction motors running at good loads while the majority may not carry good average loads. There are nearly constant loads and highly variable loads. Each case presents a different problem. In this chapter the subject is discussed in a fundamental manner rather than from a commercial basis.

92. Source of Supply of Magnetizing Current.—If the power-transmission system is new, and it is possible to put in adequate generators, transmission and distribution lines, transformers, cables, and wires to supply the magnetizing current from the main generators, it may be found cheapest and best to produce the magnetizing current at the same place where the working is produced, that is, at the central station, particularly if the transmission line and the distribution system are relatively short.

On the other hand, if a present system has reached the limit in its output or satisfactory performance, which limit might be removed by the installation of corrective devices, the problem is quite different.

Men accustomed to new industrial-plant installations can scarcely believe the conditions reported in some old plant installations. Plant engineers and electricians come and go, but the plant remains. Often such men do not know the layouts of the plant distribution systems because they are new men, no wiring diagrams exist, and they are too busy to trace them out. It is unfortunate, but true in a great many cases.

There are large numbers of consumers who use so little power, say, 100 kw. and less, that it does not pay to install present forms of metering equipment for determining the power factor.

There are large industrial plants where synchronous motors are operated directly from the utility's supply without any intermediary transformers and the consequent copper and iron losses therein.

93. Usual Conditions Reversed.—In a 250-mile transmission line, the inductive effects due to induction motors and transformers are desirable because the line acts like a static condenser. Steel wound with insulated wire and static condensers both produce reactive effects, but each tends to neutralize the other, so far as the supply voltage and working current are concerned. If there is too great a reaction from a coil wound over steel, a static condenser helps to counteract it. If there is too much reaction from a static condenser or a long transmission line, a coil wound over steel helps to counteract it. Where there is too much of the one, some of the other is beneficial.

A paper[1] by R. E. Doherty and H. H. Dewey states:

> In the case of long-distance transmission lines it is desirable, so far as the line is concerned, in order to keep the losses and regulation of the line at a reasonable figure, to deliver power at the receiving end at a high power factor. This results, however, in a high power factor on the generators at any given load and consequent lessening of their breakdown capacity. As a matter of fact, some local low-power-factor load on the bus at the generating end of a long-distance transmission system may actually increase the maximum power possible over the line by increasing the generator excitation.
>
> In this connection it will be noted that a high-power-factor load is actually a detriment in so far as it affects synchronizing power, and it is certainly one of the phenomena that should be taken into account in the design of a long-distance transmission system. It may come as somewhat of a shock to many engineers who have not made a close study of this problem, to learn that the inherent charging current of a long high-voltage line actually reduces the maximum power that can be transmitted with respect to that which could be carried over a line of similar reactance without charging current. The authors have made actual studies showing that more power could be carried over two high-voltage long-distance lines in parallel than over three with a given installed generating capacity. This is merely an illustration of the effect of

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[1] "Fundamental Considerations of Power Limits of Transmission Systems," *Journal* A. I. E. E., p. 1,045, October, 1925.

reducing the excitation on the generators by the excess charging current of the third line in a case where the impedance of the generators is an important factor.

Figure 104 will serve to illustrate this point. It will be noted that for the 250-mile, 220-kv. line considered, there is a definite relation between the installed synchronous capacity and the number of transmission circuits that will give maximum power over the system. In the case of 300,000-kva. synchronous capacity of usual design at each end of the line, three circuits will carry approximately 160,000 kw., and nine circuits no power whatever.

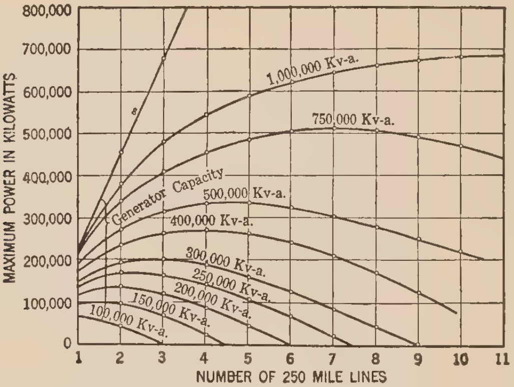

Fig. 104.—Maximum power which can be transmitted 250 miles at 220,000 volts, shown as a function of the capacity of synchronous apparatus, and the number of transmission circuits.

Figure 105 shows the effects of impedance drop which changes the magnitude, and displaces the phase, of the voltage.

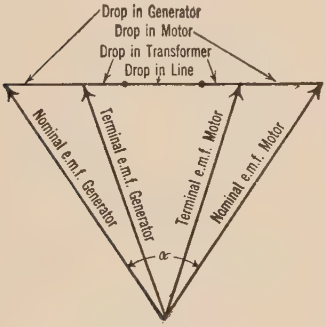

Fig. 105.—System voltage vectors.

94. General Principles.—While each problem for each system or a part of a system must be worked out separately, the general principles are given below:

Case 1. *Supply of Magnetizing Current from the Central Station.*—At first glance, this would appear to be the best way to supply the magnetizing current, along with the running current, because of the size of the generating equipment and the relatively low cost of producing the magnetizing current thereby.

It would seem that if it is cheaper to generate power at a central station than on the power user's premises, it would be cheaper to generate the magnetizing current at the central station than on the power user's premises. An argument in favor of this principle is that the total current produced by the central station is only 0.707 times the algebraic sum of the magnetizing and working currents when the two latter currents are equal to one another. Simply by way of illustration, if the magnetizing current in the central-station generator, substation transformers, secondary distribution system, and local transformers is the equivalent of 141 amperes, the magnetizing current is 100 amp., and the working current also is 100 amp., only 141 amp. need be produced by the generating station to magnetize and run the motors in an industrial plant; whereas, if only the running current was produced by the central station, there would be 100 amp. in the generators and transmission line, and so forth, to run the motors, while an additional 100 amp. would have to be generated on the consumer's premises to magnetize the motors, making the total current in the industrial plant 200 amp. The principle is illustrated in Fig. 106.

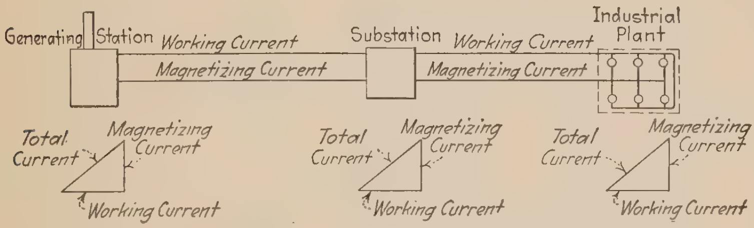

FIG. 106.—Alternating-current system. No power-factor correction.

But voltage regulation and power factor are so intimately associated that one may be as important as the other. Again, there are long lines and short lines, as hereinbefore mentioned. According to Kelvin's law, the monetary loss to the utility, passed on to the power user, varies directly as the current strength; so the cost to the utility of transmission and distribution through its lines, feeders, and transformers would be 1.41 times greater when producing both the magnetizing and working currents than when producing only the running current, and the electrical investment would be proportionately greater.

Case 2. *Supplying Magnetizing Current from the Substation.*—In this case, it may be assumed that the power factor is 100 per cent (which it is not, as a general rule) and that only the running current is supplied by the central station. With the same values for magnetizing and running current as in the preceding case, 41 per cent more working-current capacity would be available in the central-station generators and general electrical equipment, and there would be a slight saving in coal due to the lower lines losses. Furthermore, the voltage regulation would be much improved. These conditions are shown in Fig. 107.

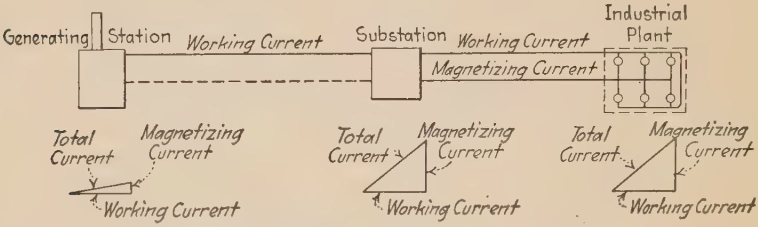

FIG. 107.—Power-factor correction at substation.

Case 3. *Supplying Magnetizing Current from the Industrial-plant Terminals.*—In this case, if all power users did it, the connection of sources of magnetizing-current supply at the plant terminals not only would relieve the central station of the burden of supplying the magnetizing current, and the transmission line of the burden of carrying it, but also would relieve the utility's transformer banks between lines and secondary distribution systems and the whole distribution system of much of the burden of carrying the magnetizing current. This is illustrated in Fig. 108.

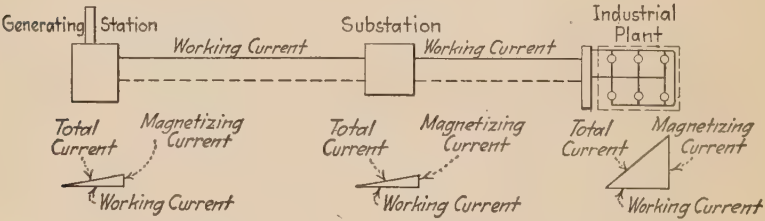

FIG. 108.—Power-factor correction at industrial plant's terminals.

Case 4. Supplying Magnetizing Current at or Near Induction Motors.—The consumer is especially concerned with this point. If such apparatus was installed on all consumers' premises right at or near the terminals of the induction motors, or a combined form of synchronous and induction motor was installed which would carry the regular loads of the motors replaced with unity-power-factor motors and simultaneously correct the low power factors due to induction motors, the consumer would also receive the benefits received by the utility in the previous cases, and the further benefits of increased production through the smoother running of machines, and so forth, as hereinbefore outlined. This condition is shown in Fig. 109, which should be compared with Fig. 110 which represents direct-current conditions.

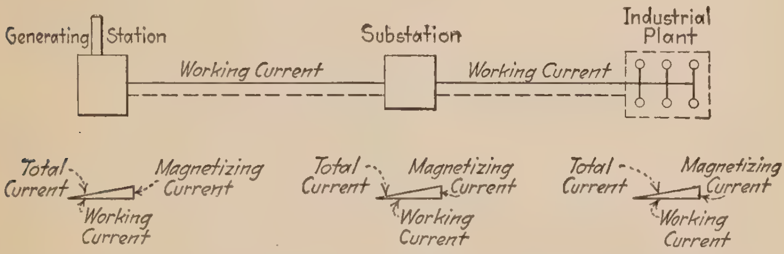

FIG. 109.—Power-factor correction at or near induction-motor terminals, either with static condensers or synchronous-induction motors running at unity power factor and correcting the power factor of nearby induction motors.

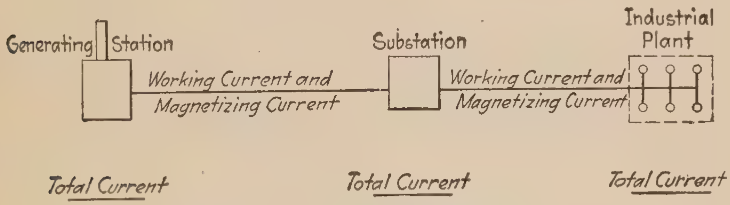

FIG. 110.—Direct-current system.

Which is the best way to go about it? All engineering details have been worked out. There are machines and devices of standard design and manufacture ready for all those who want them—synchronous apparatus for the substations and other locations, motors to replace induction motors in industrial plants and simultaneously improve the plant power factor, static condensers for connection at various locations, as at plant terminals and directly across the terminals of induction motors, or across feeders, and the like. There is no particular financial problem involved within the plant because where power-factor correction really is needed, corrective apparatus proves a good investment and can be purchased and installed piecemeal or on the installment plan in many cases.

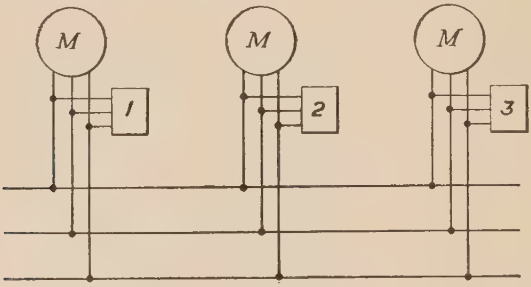

Fig. 111.—Common connections of individual static condensers.

Case 5. Mutual Reactions in Power Circuits and Systems.—Figure 111 shows three induction motors on the same main. The power factor of each is corrected by some kind of device. This circuit is the equivalent of that in Fig. 112, providing the motors and the devices are close to the main. While such devices are designed to offset the lagging reactive kilovolt-amperes of the motor to which it is connected, the corrective (leading reactive) kilovolt-amperes of each corrective device may be constant while the lagging reactive kilovolt-amperes of each motor may be variable. Therefore, leading kilovolt-amperes may pass forward all over the main and from some correc-

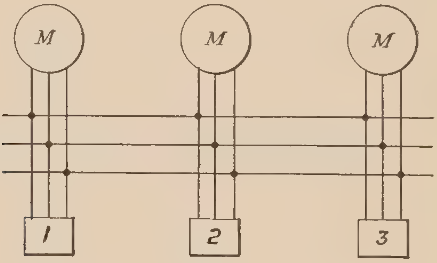

Fig. 112.—Equivalent of Fig. 111.

tive device to some motor remote therefrom. This fact should be taken into consideration, therefore, when installing such apparatus. The fact that a corrective device of whatever character is connected directly across a motor, or very near thereto, does not necessarily mean that the magnetizing current from such a corrective device is strictly confined to the motor nearest to it.

The above principle indicates that a plant with an inherently low power factor may receive the benefit of a neighbor who increases his plant power factor. However, each motor corrected performs much better than when not corrected, although the loading of an induction motor increases its power factor without any effect on other induction motors, since an induction motor does not supply magnetizing current as do power-factor-corrective devices—they require a supply of magnetizing current and are the principal cause of power-factor wastes.

CHAPTER XVIII

STATUS OF POWER-FACTOR CORRECTION

Shortly after the presentation of his paper before the New England Sectional meeting of the National Electric Light Association at New London, Conn., Sept. 10, 1925, L. W. W. Morrow, Managing Editor, *Electrical World,* presented the data for use in this and the following chapter, with the illustrations intended for, but not used in, the presentation of his paper above referred to. The illustrations have been used in Arts. 44, 51, and 65. The paper is printed in full herein.

95. Introduction.—Interest in power-factor correction is at a peak value through the electrical industry. Many properties have studied and are studying this subject as a part of their business activities, and wherever utility men congregate, it forms a topic for active discussion. It is one of the most interesting and at the same time the most difficult problems confronting electrical men.

Although years of experience with correction have been had and many data and opinions are available, it is still unsafe to draw general conclusions and no great amount of agreement exists as to its business possibilities. The encouraging aspect of the present situation is that correction is being given attention by utilities, manufacturers of corrective equipment, and power users. In fact, so much attention is being given to the subject that some executives question if this attention is justified when so many other phases of electrical business activities can be given attention with more tangible and more profitable results. Yet all agree that low power factor causes a dollars-and-cents loss to all industry and decreases the quality of electric service and of production in factories. The disagreement exists only as to the extent of these losses, the methods to use for their reduction, and the equitable division of the costs incurred for their elimination.

96. Why Low Power Factor Exists.—Low power factor exists because alternating-current equipment requires excitation as does direct-current equipment. But in the case of alternating-current equipment, this excitation is supplied from distant generating stations and is a large proportion of the working current. These large magnetizing currents clutter up the whole alternating-current system to cause losses, to decrease the economic efficiency of the installations, and to limit the quality of service rendered users of electricity. Copper losses are increased, voltage drops are magnified, and the rated capacity of generators, lines, substations, and feeders cannot be utilized for handling rated values of revenue-producing energy. Equipment users also cannot use electricity at full efficiency or with maximum economy in production processes. Thus magnetizing current is a nuisance and expense usually in all parts of the system except inside the equipment requiring it for operation.

And unfortunately, in the historical development of the electrical business, no direct commercial account has been taken of this magnetizing current. The watt-hour meters do not measure it; the rates based on kilowatt demand, and kilowatt-hours of energy neglect it; unlike the situation with respect to direct-current installations, it is not the custom to supply excitation locally at the places needed through auxiliary devices analogous to exciters; and finally, it has not been the practice to charge for or to pay for the excitation of alternating-current equipment.

Some electrical men say, why all the bother about power factor anyway? The companies are charging rates that take care of magnetizing current or they would become bankrupt. No one understands much about the subject; so why not go on as we are?

Others say, the utilities have advocated the abolition of private plants in factories in order to give better service and greater economy through central-station generation. Doesn't the same principle hold true with respect to excitation? Isn't it cheaper and better to generate it in central stations so that it can be used when and where desired on the system?

Others say, why complicate our business with power-factor rates? Rates even now are complex, multifarious, and classified like Webster's Dictionary. We have made great investments in duplicate equipments to insure service, and the properties have grown to enormous proportions. No one can make a cost analysis of a complete system for power-factor correction that means anything over a period of years; so why bother with it and why devote a lot of time to idle and fruitless discussion?

All these negative statements have been made and answered time and again, and still the subject will not down. Yet a conclusive and industry-wide decision has not been made as to the disposal of the power-factor question.

97. Use of General Statements.—A standing principle of the electrical industry is to produce, distribute, and use electricity at the lowest possible cost consistent with the best possible service. It is only natural in the light of this self-evident business axiom that power-factor correction should have received and should continue to receive executive and engineering attention. On the surface, it offers surprising possibilities. For example, a common analysis is as follows: In 1924 the central stations produced 54,000,000,000 kw.-hr. but sold only 43,500,000,000 kw.-hr. for the sum of $1,333,000,000. If it is assumed that power-factor correction would have reduced the losses the very conservative amount of 10 per cent or 5,250,000,000 kw.-hr., it is easy to compute the revenue value of the saved energy as $34,000,000. This, at 10 per cent represents a potential capital investment by the utilities of $340,000,000 to obtain power-factor correction.

Another line of reasoning is used by assuming an average metropolitan system with an annual generation of 500,000,000 kw.-hr. The capital investment of this system will be divided as follows: generating stations, 30 per cent; transmission lines, 10 per cent; substations, 15 per cent. Thus it will be noted that the investment in property other than generating stations exceeds by 50 to 75 per cent the investment in the power plants. And it is in the outside property that power-factor-improvement savings occur and where the least improvement in the efficiency of operation can be noted over a period of years. On this assumed system with 20 per cent losses in the system and with a 10 per cent reduction in these losses by power-factor correction, there results a saving of 10,000,000 kw.-hr. in losses whose cost at 1.2 cts. per kilowatt-hour is $120,000 per annum. Thus, at 10 per cent capitalization, this property can afford to invest $1,200,000 in power-factor improvement. The foregoing analyses all neglect the value of capacity released for energy sale, and this in itself often makes an item far larger than the money involved in loss reductions.

Analyses of the types noted merely give a general picture of conditions. It is a far cry from such generalizations to the actual institution of correction as part of the business activities of a utility. They serve little else than to fix conclusion that power-factor correction warrants study and offers possibilities for securing greater economy and improved service in the electrical business.

In attempts to get the most equitable distribution of costs of service and the most economical system, power-factor correction should receive detail attention on each property. There are no technical difficulties in the way of its institution. Engineers could make all systems unity power factor at command if this procedure were the economic solution to the problem. But the economic solution may not be the business solution. Thus wheels within wheels revolve about correction on every property.

It may be uneconomical to make an engineering study of correction for each system and to take advantage of every possible opportunity for power-factor correction. But it is good business to fix certain principles, methods and standards of service, and engineering practice which will fulfil a large number of the economic, business, and engineering conditions far better than guesswork methods or utter neglect of the subject. It is the business of utility executives to direct their capital and thinking to things which give the greatest returns, and this kind of approach is the only proper approach to the problems of power-factor correction.

In spite of the fact that nearly every generalization in regard to power-factor correction is subject to exception and very complicated, on individual properties utility men can quickly and easily arrive at a definite conclusion in regard to the value of correction. The safe way to find out about correction is to study it as a contemplated business activity under specific conditions.

98. The Consumer Problem.—Any study of correction must inevitably deal with the power user and his installation, for here lies the source of the trouble due to magnetizing currents. But the user of electrical energy is generally very little concerned about anything except service. The cost of power is generally a small fraction of his total cost of manufacture, electricity is an unknown entity, and he has been served so well by the utilities that he has not given much thought to power problems. His problem is one of organization for production and sale of a manufactured product.

The proper approach to the subject of power-factor correction with a user of power is the educational approach containing a selfish interest element. He must be shown that he can make a better product with less rejections in greater volume per unit of time and at a less cost if he institutes correction. He must have the correction job done for him and must have the results of the job check with the dollars-and-cents savings sheet predicted before the work was done. He must be shown how his service and that of his neighbors will be improved and the possible savings made available for all users.

Very often it is inexpedient and uneconomical for correction to be instituted on this basis. Compromise methods use penalties or bonus rates, connected-load power-factor requirements, demand charges, and other ways of forcing or inducing the user to correct his power factor. These methods do not require an analysis of production processes or of equipment installations. In a search of correction jobs on many properties and covering many customer installations, very few if any completely analyzed and solved correction jobs have been found. Correction resulted in all cases, but a more or less rule-of-thumb engineering and sales job had been done, and the complete analysis had not been made. The cost to the utilities and to the manufacturers' salesmen, as compared to the dollars returned by this kind of engineering selling, was too large.

Large manufacturing establishments with competent engineering staffs readily understand and institute power-factor correction if inducements are offered. But the many small machine, wood working, textile, specialty manufacturing, and other industries with small plants and no engineering staff as such present a very difficult problem in correction. These plants require the cooperation of central-station power salesmen, wiring contractors, and salesmen of corrective equipment to do the best job of correction. Each party to benefit from correction should receive his share of the economies obtained and bear his proper share of the costs incurred. In general, only very competent engineer salesmen can approach this kind of work intelligently.

Preposterous statements have been made and printed about the results of correction. The "overmotoring" slogan has been done to death. It must be recognized that users of motors cannot operate equipment under ideal conditions all the time.

Loads fluctuate, factory conditions change, and production requirements cannot be anticipated accurately. Also stories of speed changes of induction motors and consequent increases in production are more or less exaggerated when it is remembered that a normal induction motor has a slip of only about 4 per cent from no load to full load, and that the slip varies inversely as the square of the voltage. Very careful and accurate engineering analyses for production processes are required to give the correct story of before and after performance on a correction job. A good salesman can be very convincing to a prospective purchaser of corrective equipment, but real economic merit will eventually determine the worth of the sales talk.

Thus the problem of handling power-factor correction with customer installations becomes one of personnel and organization to do a business and engineering job intelligently and accurately within the bounds of the losses and savings made possible by power-factor conditions. Any valid correction job should save money for the utility and the consumer.

99. Successful Institution of Correction.—Any system that wishes to embark on a program of power-factor correction may do so by either: (1) the wholesale institution of correction, or (2) the piecemeal institution of correction. With either method, some preliminary work should be done if the job is to be done intelligently. This work consists of: (1) either a partial or complete engineering and economic study of the utility system to determine costs and savings due to power-factor changes, to determine conditions as to power factor and voltage at various locations, and to determine the amount and location of the different types of corrective equipment selected; (2) a study of rates for securing correction and for obtaining an equitable division of costs and savings between the utility and its customers; (3) a study of ways and means for handling power-factor correction with customers and as a part of the normal utility business; and (4) a study of the indirect elements of correction, such as the legal phases, the attitude of the regulatory commission, and the effect of correction on public relations and upon load building.

All systems can very readily institute power-factor correction on a partial or increment basis. Very little study is required to show the value of correction at substations distant from generating stations, on the premises of large power consumers at the end of long feeders, and on premises of certain classes of large power customers such as ice manufacturers, steel mills, and textile mills. Then again, if an appreciable amount of high-tension power is sold in bulk, or if a large quantity of energy is changed in frequency or type for sale purposes, an opportunity is offered for the economical institution of correction.

Some utilities go so far as to state that if correction of this character is had, there is little inducement to warrant further steps. They claim the system power factor is kept to a reasonable value by these methods without a burdensome expense in overhead and billing charges. For instance, if they can get all ice plants to install synchronous motors, can install corrective equipment at distant substations through the use of motor-generator sets and synchronous condensers, and can get a large proportion of new power customers to use synchronous or unity-power-factor motors, they feel they are getting correction cheaply and adequately.

Other systems correct by classes[1] of customers very largely. Tests and studies of power-factor correction for one factory of a class give data which can be applied pretty accurately to other factories of the same type. Once all customers of a class are corrected, it is next in order to take another class of customers and follow through the same process.

In general, they find it advisable to institute power-factor correction on a piecemeal basis in order to limit the influence of mistakes, to determine the results from trial installations, and to measure the possibilities of correction for the whole system.

The wholesale institution of correction would be necessitated by the adoption and enforcement of a power-factor-rate clause for all power customers and the institution of correction of all substations. This calls for a dive into correction with an accompanying initial cost and personnel outlay that frightens most utility executives. It has the one advantage, however, of getting results quickly and uniformly over the whole system, if it is instituted correctly. As a matter of fact, most utilities have felt their way along correction lines, and very few, if any, have attempted a wholesale basis of operation.

100. Cost Studies and Their Use.—An analysis of each system on an economic and engineering basis should be fundamental to the institution of correction. This analysis should measure existing power-factor conditions at substations, at load centers, and on customer installations. It should take into account voltage conditions, load conditions, growth conditions, and demand conditions on all feeders, substations, and large transformers. It should attempt to evaluate costs of low power factor in producing energy and capacity losses, and should fix the cost of installing and operating a corrective system for all locations.

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[1] Really sub-classes.—EDITOR.

This analysis should not be made to fix a power-factor rate on a cost-of-service basis. There are too many intangibles involved in the rates themselves and in power factor to try to use cost of service in rate making. Then again, system conditions are changing rapidly, and the whole study should deal with a period of at least five years before and after the time at which it is made.

The system analysis should be made to give fundamental cost and engineering data to determine if correction is warranted, where it can best be made, and in what kinds and amounts it is advisable to install corrective equipment at the different locations on a system. It is a basis for fixing the system power-factor conditions and for determining the moves that will give minimum overall costs and maximum service quality.

Each system differs from the others but all are going concerns; so it is not a problem of a new design of system for best and economical power factor. If generators are rated and installed on a basis of a system power factor of 80 to 85 per cent, a different condition is faced from that when generators on another system are rated and installed on a 90 to 95 per cent system power factor. It is necessary on each system to make an economic allocation of wattless kilovolt-amperes to generating stations, substations, lines, and distribution system which will take actual load conditions, distances, growth conditions, and service quality requirements into account.

The costs in a system analysis should include cost values made on an increment basis. If two cables are required for an installation instead of one cable because of low power-factor conditions, a different cost should be entered from that where simply a larger size cable is required. If two cables are required to insure service continuity, then it means a still different cost to charge against power factor. If new substations are planned to carry certain districts, their costs should be figured on a kilovolt-ampere basis determined from the total costs of stations built under two different power-factor conditions. If two transformer banks are used at a load to give service reliability, to maintain good voltage, and to care for power-factor conditions, cost analysis must take all elements of the installation into account before charges are made against low power factor.

A fundamental consideration in the study is: What is the limitation to profitable sales of energy considered under present and near-future conditions? Released capacity, if utilized for sales of energy, has no value, and so why should added investments be made to release the capacity? The business of a utility is to sell energy at a reasonable cost and of high quality. This fact should never be forgotten in internal studies of system details. Power-factor correction, if well considered, must aid this program, and a system analysis is the fundamental basis of measuring how far power-factor correction ties into this program.

101. Power-factor Rates.—A rate that will induce customers to improve their power factor is an essential aid to power-factor improvement. Its only purpose should not be to distribute costs due to low power factor nor should it be formed on a purely technical basis. A prominent utility executive has stated:

> I have very earnestly deprecated too much analysis of costs due to low power factor from a technical point of view. There are so few items that are provable in any given case and in accordance to the rules of evidence. I should be sorry to see any utility put in the position of having to make a technical defense of a power-factor clause unless the surplus of proof was so great as to be overwhelming. It would be hard for any company to prove beyond dispute the case for a general power-factor clause which resulted in a credit or debit of more than 5 per cent of its standard rate for alternating-current power service.

The exact form of rate is a matter for study and choice on each property and no very great amount of agreement exists. Of the companies having rate clauses in effect, 6 give discounts only for correction, 37 give both discounts and penalties, 48 give penalties only. These rates are shown in the following chapter. In Table XXXVII some interesting data are shown in regard to methods in use for determining power factor to which rates can be applied.

In nearly all existing rates, there are faults to be found. The ideal power-factor rate should induce the customer to raise his power factor at the time low power factor results in most damage. This may be at a peak-load period or at a light-load period, depending on the customer installation. Also this period from the standpoint of the customer may or may not coincide with the best period from the standpoint of the utility. The ideal rate should proportion costs and savings properly between the utility and the customers, and this is a condition that can be put only on an average basis. The ideal rate should be simple in form, easily understood by the customer, and readily applied to the billing and metering system.

It is no wonder that great complexity and a wide variation exist in power-factor rates in use, for attempts to meet the ideal rate in all particulars must result in compromises adapted to the conditions for each utility. A kilovolt-ampere demand rate is the simplest and easiest to institute and administer and will give an average result that will be satisfactory. It must be remembered that the economical handling of power-factor correction as a part of the business of a customer and of a utility must be based on averages and not on details and theoretical refinements.

102. Handling Customers.—A competent power salesman should be able to handle all power-factor relations with customers. The general trend to have a power salesman as consultant and advisor to his customers is along proper lines to get correction instituted most readily and with the least effect on customer relations. Very many cases can be cited where a power salesman has brought about power-factor correction to the benefit of both the utility and the consumer without the use of any form of rate clause. An intelligent salesman will handle each prospect in the best manner, and there is no general rule of approach or action. Power-factor correction can be made a normal part of the power-sales activities.

From the standpoint of the meter department, power-factor correction can become a heavy burden. It depends on the meters and metering methods adopted. In general, the more accurate the determination of power factor under all load conditions, the more complicated becomes the metering and billing system, and the more expensive it is to operate. If a very large customer is to be handled, the complication and costs may be warranted, but if small customers are handled, the complications and costs are not warranted. Thus the metering and billing system should be flexible and adapted to the classes of customers rather than rigidly standardized for all customers.

The attempt should be made to get power-factor correction with all power customers on the system if real results are to be had, and the metering and billing system should be made on this basis. Good results have been had by very simple methods. In Philadelphia, for example, a simple factory test is made under normal operating conditions before power contracts are signed. This test gives the governing conditions for billing under the contract and affords opportunity to point out to the customer his saving in power cost if he will institute correction. The cost of this type of test will not average over $8 per customer on that system. On the West Penn Power Company system, a graphic-power-factor meter is installed on the customer premises and operated only at infrequent intervals to give a fair indication of average power-factor conditions. The most complicated system requires meter panels with integrating and graphic watt-hour and reactive watt-hour meters and involves a cost and complexity warranted for very large customer installations only.

103. Intangible Elements in Correction.—The bugbear of public relations has prevented many properties from embarking upon a program of power-factor correction. This objection is mostly imaginary if correction is instituted with intelligence and a little understanding of human nature. In no case has there been any noticeable effect on public relations, and in several instances the intimate contacts brought about through the institution of correction have really improved public relations.

The attitude of public service commissions toward correction is often a stumbling block and cannot be stated in a generalization. In some instances, power-factor rates have been approved, in others rejected, and in others not acted upon. As a general practice, any fair power-factor-correction program receives the support of the regulatory commissions.

104. General Examples.—Some specific examples of correction by utilities and by consumers may serve to show how individual cases of correction may be brought about readily and with undoubted financial and operating advantages to all parties concerned in the transactions.

For example, assume that an outdoor substation fed by two high-voltage lines from two sources of power has two 15,000-kva. banks of transformers carrying a load of 14,000 kw. at 78 per cent power factor of 18,000 kva. Operating under these conditions means an overload on one bank or the operation of both banks to care for swings and load growth. Now a 10,000-kva. synchronous condenser placed at the substation would bring about a total load of 14,260 kw. at 99.3 per cent power factor or 14,360 kva. and release 3,640 kva. in transformer capacity, which is worth about $13,000, and will permit either bank to carry the load readily. The voltage drop will be changed from around 5 per cent to less than 1 per cent across the transformers. In addition, the condenser will cause a decrease in transmission-line losses, give a better voltage regulation on the line, and raise the capacity of the line about 20 per cent. Also the generating-station demand is lowered nearly 4,000 kva. which can be capitalized for at least $6,000 per year.

The total cost of the condenser will be around $50,000, and under these conditions its purchase and installation is warranted because of the savings resulting from released and needed capacity and because of the greatly improved operating-service conditions.

Another example might be studied where many conditions must be considered before a decision can be reached. A metropolitan substation load shows typical load curves which may be separated into a lighting load taken by apartment houses and office buildings, and a power load taken by small-power customers, machine shops, textile manufacturers, and others. The average power factor is about 70 per cent on the substation.

Average conditions for the year are obtained as follows: The kilowatt load factor of the average day is assumed to be the average of the monthly records. This together with the kilowatts obtained from the yearly total of kilowatt-hour substation output determines the peak load, and a curve is then interpolated between the daily load curves. A kilovolt-ampere curve is interpolated similarly on the assumption of an 85 per cent peak power factor, obtained from daily power-factor curves. The load division among feeders and transformer banks is obtained from daily load records, feeder impedances, and the normal operating schedule. The saving in losses on correction can then be based on this average day, using the actual constants of feeders and transformers.

The dollar loss indicated in correcting at the substation is due to the lighting load which is predominant at the peak and so diminishes the effect of the correction on the peak kilovolt-amperes. It points to the general conclusion that correction at a large metropolitan substation will be justified only when there results a substantial reduction in the peak kilovolt-amperes, and this can be obtained only when the power factor is quite low at the time of the peak load.

105. Correction at Customer.—Another example might be taken of a textile mill which operates a number of small motors and gives a normal power factor of 30 or 40 per cent. A contractor may have installed code wiring without considering power factor and thus the factory owner finds bad voltage conditions, high losses, fire hazards, and many other troubles to contend against when he attempts to operate.

A practical analysis shows that with or without a rate inducement the economic solution may be the use of small condensers at each motor. Some astonishing results occur and this special case proves up, but it must be remembered that it is a special case.

An instance of a type of correction which readily appeals to a power user can be provided by the application of a rate-clause analysis before the power contract is signed.

106. Available Corrective Equipment.—Corrective equipment and unity-power-factor equipment of several types and kinds have been produced by manufacturers. All this equipment can be used successfully, and while in many cases an analysis will show quickly the type of equipment to use, in other cases the decision as to type must be made a matter of very detailed analysis and the exercise of judgment.

The available equipment consists of synchronous motors, synchronous condensers, static condensers, rotary converters, phase advancers, unity-power-factor motors, and special motors of the Fynn-Weichsel type. It does not appear that any motor will replace the induction motor as the general-purpose motor in industry, and it must be conceded that the modern induction motor has a very satisfactory power factor when fully loaded. Thus other motors and corrective equipment must be used in special fields of application and as supplementary corrective devices to secure power-factor correction. In certain fields, however, motors other than induction have advantages in cost and performance over induction motors, and engineers should possess full information about them in order to apply them in their proper fields of activity.

The items to be considered in choosing between the different methods for securing correction are:

1. Investment costs of equipments and installation.
2. Operating costs.

3. Ranges in rating, power factor, control and voltage regulation effects.
4. Space requirements.
5. Duty cycle or production requirements.
6. Location of corrective equipment.
7. Advantages and disadvantages in operating and maintaining the equipment.

Linked with the choice of equipment, also, are questions of reliability, provisions for expansion or contraction in the manufacturing plant, and even flexibility in changing power equipment to conform to changing production requirements. Then arise questions as to location of corrective equipment, whether at the supply or load end, whether in the load center or at individual loads; and often starting and stopping conditions must be considered, as they may result in blowing of fuses, opening of breakers, starting of surges, the breakdown of equipment, or a slowing up of production. To cap all this, there must be agreement as to the allotment of costs and operating responsibilities between the factory and the central station.

The investment cost per corrective kilovolt-ampere is subject to several variables such as voltage, rating, frequency, range of corrective kilovolt-amperes required, type of corrective equipment, location of corrective equipment, and cost of installation. Even the basic costs applicable to the induction-motor installations may vary from $6 to $20 per horsepower, depending on the size.

The cheapest type of corrective equipment on a first-cost basis is usually the loaded synchronous motor rated at 80 or 90 per cent power factor. The size, voltage, and speed affect the cost very decidedly, and the cost to be added to the initial induction motor costs for each corrective kilovolt-ampere desired may vary from $14 for a 100-kva. machine to less than $4 for a 1,000-kva. machine.

If synchronous condensers are used, the investment charge per kilovolt-ampere will vary from $20 to $5, again depending upon size, and so forth, while a static condenser will cost from $20 to $60 per leading kilovolt-ampere, depending on voltage and size. A special corrective motor will cost from $20 to $35 per corrective kilovolt-ampere. The circuit voltage and the commercial ratings and types must be carefully considered in making such comparisons. The synchronous condenser and loaded synchronous motor is available in rating from 50 up to 40,000 kva., the static condenser from ¼ to 3,000 kva., and the special motors from 5 to 300 kva.

In comparing the static-condenser induction-motor combination costs with a Fynn-Weichsel motor or a synchronous motor, it may be noted that the cost of static condensers and the kilovolt-amperes required increases proportionately with the horsepower of the load, but that the price of Fynn-Weichsel motors and synchronous equipment increases more slowly than the horsepower capacity. This cost relation favors the Fynn-Weichsel motor or the synchronous equipment for the large horsepower loads. It must also be noted that the cost of 220-volt static condensers is almost double the cost of this equipment for 440-volt service. Starting torque and overload possibilities also often affect the rating of a motor to be used, and this fact enters into the cost analysis for many applications.

The cost of operating must be determined as well as first costs, and here the static condenser without transformers with a loss of about one-half of 1 per cent is supreme. The synchronous equipment has the usual losses incident to rotating machinery and with the usual costs for energy these losses amount to an appreciable item per year. Installation costs, space rental, and maintenance costs also must be considered before a complete cost analysis can be obtained. Very largely the size of the load, the voltage of the circuit, the load factor, and the cost of power will determine the equipment most economical to purchase and use under given conditions.

107. Effect of Line-voltage Changes.—The cost of all corrective equipment decreases at different rates up to certain limits, as the circuit voltage increases in magnitude. With loads at 220, 440, 2,300, and 6,600 volts and with substation voltages up to 220 kv., it is evident that combinations of equipment with and without transformers and accessory devices offer a large variety of cost computations.

But the regulation of a given circuit is also a very important item. It has been claimed that the greatest benefit derived from correction is obtained through improved voltage regulation.

There is no doubt that regulation is improved appreciably, but in some cases, at least, regulation improvement can be obtained more cheaply than through the use of corrective equipment.

The several kinds of corrective equipments behave quite differently under conditions where poor voltage regulation exists. Static condensers behave as do resistances, the current varies directly as the voltage, and the kilovolt-amperes are proportional to the square of the voltage.

Synchronous condensers and overexcited synchronous motors behave very differently. If the line voltage increases for a constant excitation, the current and kilovolt-ampere input fall, since the increase in line voltage is equivalent to a relative decrease in the overexcitation. If the line voltage decreases, the current and the kilovolt-ampere input increase, since the decrease is equivalent to a relative increase in the overexcitation.

Induction motors have little change in power with changes in line voltage, but the reactive component decreases rapidly with a decrease of voltage. Thus the synchronous equipment is more effective than the static condenser under variable line-voltage conditions, as its corrective effect increases more rapidly than the voltage decreases and thus comes into play when needed most if voltage drops are caused by short overloads at low power factor.

With any of the equipment, the location of the corrective apparatus on the line will have an effect on the voltage delivered which is fixed by the ratio of the reactance to the resistance of the supply circuit. If the reactance equals the resistance, the drop will be reduced about one-half, but if the reactance is low compared to the resistance, the line drop will be affected very little.

108. Effect of Load Conditions.—Very seldom is a constant load condition encountered in industry, and to this fact low power factor owes its economic importance. Loads on plants, substations, lines, and motors vary with time and in type, and corrective equipment must meet this situation.

A static condenser maintains a constant kilovolt-ampere corrective effect at all times, and this fact must be weighed in connection with their application on variable load circuits. A factory with many induction motors and transformers, if corrected to 85 per cent power factor at peak-load conditions, may operate at only 65 per cent power factor under light-load conditions. In other words, group static condensers maintain correction at all times but are rather inflexible. For an individual motor, however, a static condenser of sufficient capacity to give 85 per cent power factor at no load will maintain this power factor practically constant over the entire load range of operation of the motor across whose terminals it is connected.

Synchronous condensers and synchronous motors under conditions of constant field excitation give a very marked change in corrective effect with kilovolt-ampere input. Typical power-factor *versus* load curves show this behavior. Thus if loads fluctuate rapidly and widely, an average corrective effect is obtained only if the field is left unchanged. Also it is difficult for an operator to maintain field conditions correctly when loads change, unless in constant attendance, for no automatic adjustment device is available. Often synchronous machines are encountered in installations which are operated lagging instead of leading, through neglect or inattention on the part of the operators.

Fortunately, the magnetizing current of induction motors and transformers varies within small limits even though the energy load varies over a wide range; so a fairly constant value of corrective kilovolt-amperes can be used satisfactorily on most installations. For example, a plant may have a load varying from 4,500 to 12,000 kw. or about 150 per cent with a reactive kilovolt-ampere variation of from 4,000 to 4,560 or only 14 per cent. For these conditions, the power factor, however, will vary from 75 to 90, or 20 per cent. Thus the magnetizing current, if brought within economic limits, will automatically correct low power-factor conditions.

109. Conclusions.—The best suggestion to follow in power-factor correction under present conditions on a generalization basis are:

1. A study of each system should be made to measure conditions, to find out the economic possibilities of correction, and to ascertain the best type of correction to undertake.

2. The use of the system study should be made to get correction under existing conditions and to develop plans to see that new business is connected at the highest possible power factor.

a. A cooperative committee of the power company, contractors, architects, consulting engineers, and salesmen of electrical manufacturers should be organized to care for new business coming into the territory and see that it is correctly electrified.

b. Correction should be instituted on each system and on each customer installation to make available for sale the economic energy capacity of the equipment and to secure the best voltage regulation. Each power company should correct power-factor conditions at main distributing substations to the economic degree that they can control conditions in stations on major transmission lines and at substations to utilize the economic capacity of their equipment and to secure the voltage regulation to give the best quality in service.

c. The power company should give an inducement to existing and prospective customers to improve or maintain power factor to the degree that will give the most economical operation of the secondary distribution system and customer's installations, and the best voltage regulation for the distribution system and the customer's installation.

3. The inducement for customer correction should be a rate, and the rate should be instituted in conjunction with an educational program. A practical and reasonably effective rate is a kilovolt-ampere demand rate, and the best method of application is by classes of customers. The best time to apply this rate is at the time contracts are made or renewed.

4. Utility and industrial engineers should study power-factor correction so that they know the characteristics of the different types of corrective equipment and the method of analysis for applying the equipment to corrective jobs.

5. Any corrective rate should be enforced intelligently and impartially. A sales, metering, and business personnel competent to handle this aspect of the business should be developed and trained by the power company.

6. The degree to which attention should be given to correction by any utility depends on the returns that will come to it and its customers in dollars and in service. All utilities and customers should keep power factor in mind at all times in order to keep the system responsive to possibilities for improving power-factor conditions.

7. The national status of power-factor correction is encouraging, and better power-factor conditions are being brought about by corrective work. Producers and users of electrical energy now "think" power factor in connection with their business activities, and this healthy state of mind should be maintained. Power-factor correction is good business and worthy of attention.

CHAPTER XIX

STATISTICAL DATA

In the present chapter, statistics regarding the electrical public utility companies as to methods of determining power factor, those giving discounts or bonuses and penalties, executive opinions of correction and some letters in reply to the questionnaire submitted by L. W. W. Morrow, who supplied all the data for publication herein, are given.

110. Tables.—The following tables cover the statistics above outlined.

Table XXXVII.—Methods of Determining Power Factor

1. Monthly by computations from watt-hour and reactive watt-hour meters:
    - *a.* Connecticut Light and Power Company
    - *b.* Meriden Electric Light Company
    - *c.* Rockford Electric Company
    - *d.* Northern Indiana Gas and Electric Company
    - *e.* Sioux City Gas and Electric Company
    - *f.* Syracuse Lighting Company
    - *g.* Columbus, Delaware, and Marion Electric Company
    - *h.* Duquesne Light Company
    - *i.* Pennsylvania Power and Light Company
2. By method 1 or by other methods at option of company:
    - *a.* Charleston Consolidated Railway and Lighting Company
    - *b.* Wisconsin Gas and Electric Company
    - *c.* Wisconsin Power and Light Company
    - *d.* Milwaukee Electric Railway and Light Company
3. By test, by measurement with permanent meters or by method 1:
    - *a.* Counties Gas and Electric Company (over 75 hp. by method 1)
    - *b.* Indiana Service Corporation
    - *c.* Wilmington and Philadelphia Traction Company

Sixteen companies supplying 28 out of 308 large cities specify how power factor is to be determined.

Table XXXVIII.—Companies Giving Power-factor Discounts Only

1. Rockford Electric Company—Over 50-hp. installations. General power. Intermediate power. Large and off-peak power discount: 5 per cent from net bill if power factor is maintained at not less than 80 per cent; 10 per cent if power factor is maintained at 90 per cent or better.
2. Atlantic City Electric Company (Opt.)—Large lighting and power discount: 5 per cent if synchronous motors or static condensers are used as specified by company.

3. Peoples Gas and Electric Company (Oswego, N. Y.)—General power. Discount for 3 hp. or over. Customers guarantee power factor of not less than 85 per cent. For better power factor the following discounts on net bill apply:

Continuous Power Factor, Per Cent	Discount, Per Cent
85	none
90	1
95	2
100	3

4. Columbus, Delaware, and Marion Electric Company—Large power (10,000 kw.-hr. monthly and over) discount: where customer has synchronous motor or motors of 25 hp. or more each, operating at power factor of 90 per cent or better, discount of 5 per cent from bill for energy used by such motor or motors.
5. West Penn Power Company—General power (not off-peak power) discount: 5 per cent deducted from kilowatt-hours for leading power factor of 90 per cent or less. Also demand taken in kilowatts.
6. Monongahela West Penn Public Service Company—Large power discount: 5 per cent if customer installs and operates synchronous motors as specified by company.

TABLE XXXIX.—COMPANIES GIVING BOTH DISCOUNTS AND PENALTIES FOR POWER-FACTOR CORRECTIONS

1. If the average power factor is more than 85 per cent, the demand for billing is adjusted to 85 per cent. If the average power factor is less than specified below, the demand is adjusted to the following power factor: 80 per cent at the time of maximum demand, 70 per cent average:

a. Connecticut Light and Power Company—Large power.
b. Meriden Electric Light Company—Large power.
c. Northern Indiana Gas and Electric Company—Primary power (adjusted for 75 per cent average instead of 70).
d. Charleston Consolidated Railway and Lighting Company—Large power.

2. The average power factor is determined monthly and the kilowatt-hours consumed are multiplied by a constant for billing purposes:

Average Power Factor, Per Cent	Constant
100	0.951
95	0.965
90	0.981
85	1.000
80	1.023
75	1.050
70	1.0835
65	1.1255
60	1.1785
55	1.2455
50	1.3335

a. Indiana General Service Company—Large power.
b. Indiana & Michigan Electric Company (Opt.)—Large power.
c. Ohio Power Company—Large power.
d. Scranton Electric Company—Large power.
e. Wheeling Electric Company—Large power.
f. Ohio Public Service Company—Large power.

3. The demand is corrected to 85 per cent power factor for billing purposes:

a. Indiana Service Corporation (Opt.)—General power.
b. Indiana & Michigan Electric Company—General and primary power.
c. Ohio Public Service Company—High-tension power.
d. Cleveland Electric Illuminating Company (90 per cent)—Railway and commercial power.
e. Erie County Electric Company (80 per cent)—Bus-bar primary power.
f. Citizens Light and Power Company (Opt.)—Large power. (Leading power factor is same as 100 per cent power factor.)
g. Wisconson Traction, Light, Heat, and Power Company (80 per cent)—Large power.
h. Wisconsin Gas and Electric Company (80 per cent)—Primary power.
i. Milwaukee Electric Railway and Lighting Company (80 per cent)—Primary power.
j. Wilmington and Philadelphia Traction Company (Opt.)—Large power (Leading power factor is same as 100 per cent power factor).

4. Miscellaneous rates:

a. Idaho Power Company—Intermediate and large power.
For synchronous motors the demand is increased or decreased ½ per cent for each 1 per cent the power factor is above or below 80 per cent.

b. Sioux City Gas and Electric Company—Large power.
Demand for billing is increased 1 per cent for each 1 per cent the average power factor is below 70 per cent and decreased 1 per cent for each 1 per cent the power factor is above 85 per cent.

c. Queens Borough Gas and Electric Company—Primary power.
If the power factor is maintained at 95 per cent or better, discounts are as follows: 0.2 ct. per kilowatt-hour for consumption between 30,000 and 100,000 kw.-hr., 0.3 ct. for consumption over 100,000 kw.-hr. If power factor falls below 80 per cent, the demand is taken as 80 per cent of the kilovolt-amperes for billing.

d. Syracuse Lighting Company—Large power.
When the average power factor is below 70 per cent, the demand is adjusted to 70 per cent for billing. If the power factor is above 85 per cent, the demand is adjusted to 85 per cent.

e. Cleveland Electric Illuminating Company (Opt.)—Commercial power and lighting.
Discount and penalty where power exceeds 50 per cent of connected load and billing demand exceeds 75 kw. Demand is adjusted to

75 per cent power factor for billing if the power factor is above 75 per cent. Demand is adjusted to 60 per cent power factor if the average power factor is below 60 per cent.

f. Ohio Public Service Company—Primary power.
If the average power factor is more than 90 per cent or less than 80 per cent, the demand is multiplied by 85 per cent and divided by said power factor.

g. Columbus, Delaware and Marion Electric Company—High-tension power.
A deduction or addition of 1 per cent of bill is made for each 1 per cent the average monthly power factor is above or below 85 per cent.

h. Toledo Edison Company—Primary power.
If the power factor is over 85 per cent or under 75 per cent, the demand is adjusted to 80 per cent.

i. Pennsylvania-Ohio Power and Light Company—General and primary power.
If the average power factor is greater than 85 per cent lagging, the demand is adjusted to 85 per cent (leading power factor is same as 100 per cent). If the power factor is less than 75 per cent lagging, the demand is adjusted to 75 per cent.

j. Pennsylvania Edison Company—General power. Newcastle Electric Company—General and primary power.
If the average power factor is over 90 or under 80, the demand charge is increased in the same ratio as 80 per cent bears to the actual power factor. Where the demand is over 100 kw., the customer must guarantee a minimum power factor of 80 per cent. Motors over 75 hp. must be synchronous.

k. Erie County Electric Company—Primary power.
A credit or penalty of 0.5 ct. per kilowatt of demand for each 1 per cent the power factor at time of demand is above or below 80 per cent (up to 100 per cent).

l. Counties Gas and Electric Company—General power.
The bill is decreased by 1 per cent for each 1 per cent the average power is above, or increased one-half of 1 per cent for each 1 per cent the average power factor is below:
80 per cent for installations of 75 hp. or less.
85 per cent for installations of 76 to 400 hp.
90 per cent for installations of 401 to 1,500 hp.
95 per cent for installations of 1,501 hp. and over.

m. Philadelphia Electric Company—Small, general, and primary power.
If the power factor is less than specified below, the demand for billing may be adjusted to the power factor specified:
80 per cent for demand less than 50 kw.
90 per cent for demand of 50 to 1,000 kw.
95 per cent for demand over 1,000 kw.

n. Duquesne Light Company—Commercial light and power.
Base power factor is 75 per cent. For other power factors, gross bill is adjusted as follows: A deduction or addition of 1 per cent for each reduction or increase of 10 points in the ratio of reactive to active kilowatt-hours (maximum discount 8.819 per cent).

o. Shenango Valley Electric Light Company—General power. Demand adjusted to 85 per cent if power factor is greater than 85 per cent (up to 100 per cent). Demand is adjusted to 75 per cent if the power factor is less than 75 per cent for high-tension power. Demand is adjusted to 75 per cent if the power factor is over 75 per cent. If the power factor is less than 60 per cent, the demand is adjusted to 60 per cent.

p. Wisconsin Public Service Corporation—Large power. If the average power factor over 5-min. interval of load of at least 75 per cent of demand and at least 10 kw. is less than 75 per cent, the demand for billing is adjusted to 75 per cent power factor.

TABLE XL.—COMPANIES GIVING POWER-FACTOR PENALTY ONLY

1. If the power factor is less than 80 per cent, the demand is adjusted to 80 per cent for billing purposes:

a. Mobile Electric Company (Opt.)—Large power.
b. Arkansas Central Power Company—Large power.
c. Colorado Springs Light, Heat & Power Company—Large lighting and power.
d. Southern Colorado Power Company—Large power.
e. Idaho Power Company—General power.
f. Quincy Gas, Electric & Heating Company—Large power.
g. Topeka Edison Company—Large power.
h. Louisville Gas and Electric Company—Large power.
i. Worcester Electric Light Company—Large power.
j. Beverly Gas and Electric Company—General power.
k. Fitchburg Gas and Electric Company—Primary power.
l. Haverhill Electric Company—Primary power.
m. Malden Electric Company—Primary power.
n. Salem Electric Lighting Company—General power.
o. Carolina Power and Light Company—General power.
p. Union Light, Heat, and Power Company—Large power.
q. Hamilton Electric Service Company—General power.
r. Ohio Gas and Electric Company—Large power.
s. Harrisburg Light and Power Company—Primary power.
t. Metropolitan Edison Company—Large power.
u. Blackstone Valley Gas and Electric Company—Large power.
v. Tennessee Electric Power Company—Large power.
w. Knoxville Power and Light Company—General power.

2. If the power factor is less than 85 per cent, the demand is adjusted to 85 per cent for billing purposes:

a. Kansas Gas and Electric Company—Oil-field power.
b. Minnesota Power and Light Company—Primary power.
c. New York Edison Company—Primary power.
d. Pennsylvania Power and Light Company—Large and primary power.
e. Fort Worth Power and Light Company—Refrigeration.
f. Northern Power Company—Primary power.

3. The demand for billing purposes is increased 1 per cent for each 1 per cent the power factor is below (*a*) 85 per cent, (*b*) 80 per cent, (*c*) 75 per cent:
    (1) Connecticut Power Company (*c*)—General power, off-peak power.
    (2) Stamford Gas and Electric Company (*a*)—General power, primary power.

4. If the power factor is less than 90 per cent, the demand for billing purposes is adjusted to 90 per cent power factor (*a*), to 75 per cent (*b*):
    (1) Illinois Power and Light Company (*a*)—Large power.
    (2) Concord Electric Company (*b*)—General power.
    (3) Lockport Light, Heat, and Gas Company (*a*)—Intermediate and primary power.
    (4) Union Gas and Electric Company (*b*)—Small and large power.
    (5) Washington Water Power Company (*b*)—Irrigation.

5. If the power factor is less than (*a*) 80, (*b*) 85, (*c*) 75, and (*d*) 90 per cent, the demand for billing purposes is taken as (*a*), (*b*), (*c*), or (*d*) of the kilovolt-amperes:
    (1) Cambridge Electric Light Company (*a*)—Primary power.
    (2) Buffalo General Electric Company (*d*)—Primary power.
    (3) Elmira Water, Light, and Railroad Company (*a*)—Primary power.
    (4) Queens Borough Gas and Electric Co. (*a*)—Primary power.
    (5) Eastern Texas Electric Company (*a*)—Large power.

6. Special rates:
    a. Great Western Power Company—Electrochemical and electrometallurgical.
    A charge of 3 cts. per kilowatt of demand for each 1 per cent the power factor is less than 100 per cent down to a power factor of 95 per cent; plus 4 cts. per kilowatt of demand for each 1 per cent the power factor falls below 95 per cent down to a power of 90 per cent; plus 6 cts. per kilowatt of demand for each 1 per cent the power factor is below 90 per cent down to 85 per cent.
    b. Connecticut Light and Power Company—General power. A charge of 0.025 ct. per kilowatt-hour for each 1 per cent the power factor is below the following: 85 per cent at time of maximum demand, 75 per cent average.
    c. Gary Heat, Light, and Water Company—General and primary power.
    Demand Charge $1.75 per kilowatt if power factor is over 80 per cent.
    Demand charge $2 per kilowatt if power factor is between 65 and 80 per cent.
    Increase last charge by 1 per cent for each 1 per cent the power factor falls below 65 per cent.
    d. Cumberland County Power and Light Company—Large power.
    Narragansett Electric Lighting Company—Large power.
    Customer agrees to maintain a power factor of 80 per cent from 7 a.m. to 6 p.m. on week days. If he does not make changes on request after three-month period, the demand charges are increased as follows:

100 per cent when the power factor is 50 per cent or less.
60 per cent when the power factor is 51 to 60 per cent.
30 per cent when the power factor is 61 to 70 per cent.
15 per cent when the power factor is 71 to 74 per cent.
7.5 per cent when the power factor is 75 to 79 per cent.

e. Luzerne County Gas and Electric Company—Large power.
If the power factor is less than 80 per cent, a charge of $1.20 per kilowatt is made for each kilowatt of demand difference between the demand adjusted to 80 per cent power factor and the measured demand.

f. South Carolina Gas and Electric Company—Refrigeration.
If the power factor is below 85 per cent, the bill is increased ½ of 1 per cent for each 1 per cent the power factor is below 85 per cent.

g. Houston Lighting and Power Company—Large power.
The demand is adjusted to 85 per cent power factor, after notification to change, the energy charge also is adjusted to 75 per cent power factor.

h. Wisconsin Public Service Corporation—Large power.
If the power factor over a 5-min. interval of load of at least 75 per cent of demand and at least 10 kw. is less than 75 per cent, the demand is adjusted to 75 per cent.

TABLE XLI.—UTILITY EXECUTIVE OPINIONS OF CORRECTION

These are based on experience with actual operation of power factor correction on properties which have instituted correction.

1. Is a rate clause essential to power-factor correction?	Yes 19, No 1
2. Type of rate favored:	
Power-factor clause	6
Demand clause	12
Consumption and demand clause	1
Power-factor and demand clause	1
3. Detail of rate favored:	
Penalty only	4
Bonus only	2
Penalty and bonus	11
No inducement	3
4. Correction should be applied to:	
Only primary or high-tension power	3
Large power users only	16
All power customers	4
5. Methods favored for determining power factor:	
Actual test	4
Estimate	1
Integrating watt-hour and reactive watt-hour meters	10
Graphic power-factor meters	5

Graphic watt-hour and reactive watt-hour meters	5
Kilovolt-amperes demand only	3
6. Has an analysis of system been made to determine cost of low power factor and value of correction?	No 9, Yes 6, Partially 5
7. Where should correction be made:	
Only customer premises	6
Only substations	1
Both substations and customers	13
8. Is power-factor correction a profitable business activity?	Yes 11, No 3, Can't say 6
9. Has power-factor correction affected public relations?	No 13, Yes 2, Can't say 5
10. Do you find it necessary to train men for handling customers on power-factor correction?	No 9, Yes 8
11. Has system power factor been improved?	Think so 6, Know so 6, Can't say 4, No 2
12. Should each utility institute power-factor correction as a part of its business?	No 0, Yes 16, Can't say 2, Depends on local conditions 2
13. Do you enforce your power-factor rates completely?	No 8, Yes 12

14. General remarks:
    (1) Believe kilovolt-ampere demand the best basis to secure correction.
    (2) Under our previous demand rate with power-factor clause we found enforcement difficult due to the psychological effect of tempering with the meter reading instead of direct billing. We have changed to a kilovolt-ampere demand rate which gives promise of power-factor and load-factor improvement.
    (3) About 30,000 kva. in corrective equipment has been installed by customers since we instituted power-factor charges.
    (4) Poor power factor should not be tolerated by any utility today but correction above 80 to 85 per cent is of small value.

111. Some Replies in Full to Mr. Morrow's Questionnaire.

The Detroit Edison Company
2000 Second Avenue
Detroit, Mich.

1. I think that a rate clause is essential to power-factor correction because without a rate clause there will be no commercial inducement to improve the power factor of the individual customer.

2. I prefer a power-factor clause to taking any step toward departure from kilowatt measurement of demand.

3. I prefer bonus only. My idea is that each company, when rate reductions are in contemplation, will see the importance of making rate reductions to the alternating-current consumers dependent upon good power factor.

4. In the first place, and probably for a long time to come, a power-factor clause should apply only to large users of service, without considering whether the use of the service is for power or light. Where there is a differentiation between power rates and lighting rates, I should apply the power-factor clause to the power-rate schedule alone.

5. In determining power factor, I prefer the use of a reactive watt-hour meter, in addition to the regular kilowatt-hour meter.

6. We have made no complete analysis. We have made a number of partial analyses.

7. The correction should be made, to begin with and for many years to come, along the lines where the expenditure will produce the largest results. Corrections at substations are indicated as the place where most good can be done at the present time, with correction on the premises of the larger customers as a contemporaneous process.

8. Under our existing conditions, power-factor correction is a very minor business activity having little merit as a business activity. We could put the same amount of business effort to a better use elsewhere.

9. Power-factor correction, along the lines suggested in the preceding answers, has not had any effect on public relations. Power-factor correction carried into our relations with the smaller users of alternating-current motors would certainly have large possibilities of making trouble. These people want to go on with their own day's work and don't want to worry about anything except the continuity and the cost of their power supply.

10. Our policy is to handle all dealings with customers through the sales department. It results that any sales-department employee who has to deal with a power customer will have to be trained in our power-factor policy.

11. Our system power factor is affected by so many other and larger considerations that the result of the work done thus far in the improvement of the power factor on customers' premises cannot be discovered or identified in system measurements. But the use of rotary condensers in substations has been exceedingly helpful and we are committed to a large increase thereof.

12. I think it is up to each utility to settle its own business problems according to the merits thereof. I don't think there is any *duty* laid upon any utility to improve its power factor if it prefers to let it remain somewhat sloppy.

13. Our power-factor clause carries a bonus, but not a penalty. Naturally, our sales department sees to it that every customer who

does earn the bonus, and who can earn the bonus, shall get what is coming to him.

14. I am decidedly hopeful of improvement in the average power factor of all the alternating-current motors to be built by first-class manufacturers within the next few years. Good power factor is already a selling point in a business which is strongly competitive. A great deal can be done not only along the lines in which progress has been made and advertised, but along other lines, one of which is indicated by the strong probability that there will be before long a production in quantity of a cheap and reliable condenser.

The inertia of the power-using customer, whether he be a large user or a small user, is the greatest difficulty in the way of power-factor improvement. He does not want to be troubled about anything excepting his own job, which is to produce and market something, toward which purpose the use of alternating current is necessary or expedient. He does not care a hang what the power is, so long as it is reliable and does not cost him too much either in money or in supervision. In brief, the average manufacturer feels no call to recognize the essential difference between a kilovolt-ampere and a blastoderm, and he does not care to be introduced to either of the critters. You have to show him that he will make a considerable amount of money or avoid considerable loss by improving his power factor, and you have got to make the demonstration quite clear. Otherwise, he will feel that you have been taking him away either from his business or from his golf, and will be peevish accordingly.

Yours truly,
Alex Dow
President

American Gas and Electric Company
30 Church Street
New York

I am in receipt of your inquiry pertaining to power-factor correction in the operation of industrial customers of utility companies. I do not believe that anywhere in the United States you will find at the present time power factor considered of such vital importance in the sale of electric energy to customers as in the rate tariffs of the subsidiaries of the American Gas and Electric Company.

For about seven years, we have been working under tariffs wherein power factor is brought into effect in practically all of our properties. I am attaching hereto a copy of our usual type of schedule which varies only in its charges and not in its principle in the various states in which we do business. We have this tariff in effect in Illinois, Indiana, Ohio, New Jersey, West Virginia, and Pennsylvania.

Some two or three years ago, I had occasion to outline in detail the reasons for the choosing of this type of tariff and the results that we obtained, and I beg leave to quote from this outline, thinking that the information will be of interest to you:

The rate that we have in force has proved so satisfactory both to ourselves and to our customers that we are putting it into force at every opportunity in place of some other schedule.

The tariff is made up of two parts: first, the primary portion. We have assumed that a customer to whom we sell power would have to provide a certain amount of capacity to take care of his requirements if he put in his own plant, and that the power factor of his installation would determine the capacity which he would have to install and, therefore, under the rate, we have asked him to contract for this capacity. In other words, if the John Jones Shoe Company had 1,100 hp. in small motors connected, and the demand of this installation was 600 kw. operating at an average power factor of 80 per cent, this company would have to install at least one 750-kva. generator to take care of this load. Of course, we realize that if the customer were putting in his own plant, he would undoubtedly have to have more than the above amount, but he would at least require 750 kva. Therefore, our tariff is built up on the assumption that we will go to the customer and say:

You require 750 kva. of capacity because you have a demand of 600 kw. at 80 per cent power factor. We will allow certain excess demands over and above this amount for certain periods of time (these excess demands are shown on the second sheet of the tariff) and we will limit these excess permissible demands, if necessary, by a current-limiting relay set for the proper load and the proper time limits.

We will charge you for the capacity so contracted for, a certain number of dollars per month per kilovolt-ampere of that capacity, and you will pay for that capacity each month during the year regardless of whether your demand equals it or not, because we have set aside in plant, line, and substation an equivalent amount of capacity to supply you. This monthly charge in dollars is equivalent to the fixed charges you would have to pay on a plant of your own of this capacity, whether this plant operated or not. (In some of our tariffs we have made a charge according to the hours use of this capacity expressed in kilowatt-hours rather than a straight dollar rate per kilovolt-ampere of such capacity.)

When we first began using this type of tariff some years ago, we attempted to use the General Electric relay, style CB-1, for limitation under the tariff of the customers' contract capacity. We did not find these relays entirely satisfactory and we have substituted therefor maximum-demand indicators from which we can check a customer's requirements.

If the customer, by the use of static or synchronous condensers or synchronous apparatus of any type, can better the general overall power factor of his installation, he can then contract with us for a less amount of capacity. In other words, it puts it absolutely up to the customer to purchase from us a firm capacity in kilovolt-amperes commensurate with his requirements under the best possible conditions of power factor that he can create.

The secondary portion of the tariff constitutes the second part of our charge on a basis of power factor.

The usual methods of measuring kilowatt-hour consumption is used, but we also install reactive volt-ampere-hour meters which, as you know, are nothing more or less than integrating watt-hour meters set around through the proper phase angle with the proper impedance.

With the combination of these two instruments, we can readily ascertain the average *period* power factor, and by period I mean average daily, monthly, or yearly power factor.

Our assumption in the building up of this tariff has been that in the primary portion the customer has taken care of our capacity in plant, lines, and substations in so far as power factor affects the same, but has *not* compensated us for increased losses in lines, substations, and generating equipment due to low power factor.

We have assumed that standard equipment such as most installations consist of is designed to operate at approximately three-quarter load at 85 per cent power factor, and we have chosen this point as the basis of our rate and have assumed that *we* should bear the cost of losses in the delivery of energy to the customer at 85 per cent power factor. If the customer's average power factor on his installation is less than 85 per cent, our losses in line, substation, and generating equipment will be increased over and above what those losses would be at 85 per cent power factor, and the customer should, therefore, be penalized for this increased loss or should pay for it.

Should the customer's average power factor be above 85 per cent, our losses in line, transmission, and generating equipment are cut down compared with what they are at 85 per cent, and therefore, the customer should be given the benefit of reducing these losses.

We have built up the table shown in Par. *A* of the average monthly power factor of the customer's installation and the constant by which his consumption should be multiplied at these various power factors to compensate us for power factors lower than 85 per cent and to compensate the customer for keeping his power factor better than 85 per cent. These constants were not arrived at in a haphazard manner. A formula was calculated which eliminated length of line, size of wire, etc., and which represents the percentage increase in losses at other power factors than 85 per cent as compared with the losses at 85 per cent power factor. This formula is based also on the assumption of transmission line of efficiency of 85 per cent. We have had this formula checked and we are confident that it is correct. What we have assumed really is that if we had an installation of 1,000 kva. operating at 65 per cent load factor and 85 per cent power factor and our losses were 45,000 kw.-hr., if the installation were operated at 80 per cent power factor, our losses would be 2.3 per cent of the total consumption used higher than they would be at 85 per cent power factor, and we, therefore, had multiplied customer's consumption by 1.023 in order to arrive at the kilowatt-hours he should pay for.

It is, of course, true that our losses are greatest when the customer is operating at the lowest power factor, and yet it is also true that the customer can probably create his highest power-factor condition at the time of his maximum load. We were, at first, quite undecided as to the time at which to take this power factor for correction purposes. After a lot of study, it was thought that the average monthly power factor would give the customer a chance to better his own condition and would not bring into the tariff a lot of unusual conditions for a lot of unusual loads, and that we would gain by the use of this method in this way:

If all of our customers on a given feeder maintained an average power factor better than 90 per cent, our general overall average power factor on that feeder would probably be somewhat higher than 90 per cent due to the fact that some of the customers would be operating at a very high if not leading power factor for a comparatively small load. You can readily see that a customer could operate for eight hours a day at a fixed demand at 80 per cent lagging power factor and then could operate sixteen hours a day at half that demand at 80 per cent leading power factor to an average of unity power factor and yet, under this condition, at the time of the customer's biggest load, he would be operating at a lower power factor than we desired.

Even with all these disadvantages, we decided that we would make the test as to whether average monthly power factor was the most usable scheme. The results obtained have convinced us that this method is the most practical.

There are certain other features in the tariff which may or may not interest you. The first of these is Par. *B*, covering a reduction to the customer if he provides his own transforming equipment.

Our general transmission voltage is 66,000, and if the customer has his service measured on the 66,000-volt side of the substation, we reduce the consumption of energy that he is billed by 5 per cent to cover losses sustained by him instead of by us in the substation.

Under Par. *C*, we have also given the customer certain credits. If he purchases and installs a substation from 66,000 volts down to the voltage which he uses, we are relieved of certain capital expenditures and we have built up certain credits per kilovolt-ampere of capacity of this substation equipment. These credits were based upon the fixed charges that we would have to stand had we purchased and installed this equipment. In other words, the customer relieves us of certain capital expenditures and certain fixed charges on these expenditures, and, inasmuch as our rates are based on the fact that we have to make these expenditures and stand these fixed charges, we have given the customer a credit on his monthly bill if he provides the equipment and stands the fixed charges and maintenance.

I hope that I have made this clear to you. It is somewhat difficult to describe all these details by correspondence, and the tariff looks a lot more complicated than it really is. We were fearful, at first, that we would have some trouble in explaining its feature to our customers but we soon found out that this was not so. Of course, the tariff is limited to customers who contract for over 100 kva. of capacity and usually, in clients of this type, there is someone connected with the concern who can readily grasp the features of the tariff.

It may interest you to know that in one locality where we had about 125 customers ranging from 100 to 2,500 kw. of demand, with the entire requirements for the territory some 28,000 kw., within a year and a half after this tariff was put into force, our general overall power factor for the territory increased from in the neighborhood of 72 per cent to approximately 91 per cent and that the actual kilowatt station demand increased approximately 12 per cent, all this without any loss in revenue and with the individual customers in many cases much better satisfied, due to the fact that the bettering of their power factor on their own installations bettered their own voltage regulation, cut down the losses inside their installations and, in general, greatly satisfied them.

Nevertheless, the results of the application of this tariff convince us that average monthly power factor is probably the most satisfactory way to correct additional losses caused by poor power factor.

I have given you this at length because I am of the belief that this matter of power factor is vital to central stations, more particularly to those operating transmission systems of great extent consisting of small- or medium-sized population units.

Of course, a large city where the lighting load is predominant and where the transmission and distribution are not excessive in length, has not in the past had to worry about power-factor conditions, and yet I know of one system operated by a very large company in the East where a customer, whose maximum demand was well over 5,000 kw. at approximately 75 per cent power factor, found it advantageous to install corrective apparatus to bring his power factor of the entire installation up to 95 per cent, simply for the purpose of bettering his voltage regulation on that particular feeder from which he was supplied and, therefore, automatically increasing the output of his motor-driven manufacturing equipment.

This customer received no credit from the central station for bettering his own power factor and automatically that of the feeder, and yet, had this central station had in effect a power-factor tariff, it is probable that the service rendered this customer would have been very much better and that the central station would also have been relieved of further expenditures to bolster up this particular feeder.

I am attaching hereto direct answers to your questions, included in your letter of July 29.

Very truly yours,
H. M. Sawyer
General Contract Agent

Table XLII.—American Gas and Electric Company—Reply of H. M. Sawyer to Mr. Morrow's Questions

Question	Answer
1. Do you think a rate clause is essential to power-factor correcton?	Yes.
2. In a rate clause do your favor: *a.* A power-factor clause as such? *b.* A demand clause which takes power factor into account?	
3. If a power-factor clause is used do you favor: *a.* Penalty only? *b.* Bonus only? *c.* Penalty and bonus?	Penalty and bonus.
4. Do you think power-factor rates as such should be applied to: *a.* Primary or high-tension power users only? *b.* Large power users only? *c.* General power? *d.* Larger users of both power and light? *e.* All power customers?	It is my belief that in so far as possible power-factor rates should apply to customers having at least 50 hp. connected. If it were not for the fact that the metering installation is so costly, I should favor power-factor correction to even smaller customers and I am firmly convinced that the day will come when installations of 5 hp. or more will have power-factor clauses included in the tariffs under which they are supplied.
5. In the determination of customers' power factor do you favor: *a.* Monthly tests? *b.* Estimate based on type of load?	

c. Use of integrating watt-hour and reactive watt-hour meters?	
d. Use of graphic power-factor meters?	
e. Use of graphic watt-hour and reactive watt-hour meters?	The use of integrating watt-hour and reactive watt-hour meters.
6. Have you made an analysis of your system to determine costs of low power factor and of the value of correction?	Yes.
7. Do you think correction should be made: *a.* On customers' premises only? *b.* In substations only? *c.* In substations and on customers' premises?	As far as tariffs are concerned, correction should be made on the customers' premises only, but, of course, with large high-voltage transmission systems, it is ofttimes necessary to have synchronous condensers located at strategic points on such a system.
8. As a business activity do you find power-factor correction profitable to institute and administer?	Yes.
9. Do you find it advisable to train certain men to deal with power-factor correction and with customer relations on this subject?	Due to the fact that we have had power-factor correction in our tariffs for many years, our Power Sales Engineers are thoroughly conversant with the benefits both to the company and to the customers of power-factor correction and with customers relations on this subject.
10. Has power-factor correction affected public relations appreciably?	Due to the fact that many of our customers purchase energy from other utility companies not associated with us, we have had some trouble in convincing the customer of the advisability of power-factor correction and of convincing him as to the fairness of power-factor correction as against non-requirement of this correction by other utility companies, and yet after correction has been enforced, I believe our relations with our customers have been bettered.
11. *a.* In your experience with correction have you been able to improve the system power factor appreciably?	Yes.

b. Can you show definite and quantitative results to substantiate the conclusions made in (*a*)?	Yes. In answer to (*b*) of 11, I would like to give just some general figures pertaining to one town of about 75,000 population. The installation of power-factor correction in power tariffs in this town relieved the utility company of an extremely heavy expenditure, running into many thousands of dollars, in the rebuilding of its power feeders order to maintain voltage at customers' receiver end.
12. Do you think power-factor correction should be instituted in some form by every utility as a part of its business activities?	Yes.
13. Do you enforce your power-factor clauses or rules completely?	Yes. In further answer to 13, I am sincerely of the belief that if power-factor clauses are included in tariffs at all, they should be completely enforced; any let-up in the enforcement of the same tends to destroy the value of the clauses.

H. M. Sawyer
General Contract Agent

CHAPTER XX

GENERAL AND SUMMARY

If the foregoing chapters have been read, it is believed that a fairly comprehensive idea of the power-factor situation has been obtained, even though there may be many differences of opinion. There are a great many divergent conditions which make statements by one person seem at variance with the ideas and experiences of others. There appears to be a general admission that low power factor causes poor voltage regulation and various capital and operating losses. Power-factor correction has been successfully instituted by a number of utilities and consumers. There are, on the open market, synchronous motors and other motors which not only operate at unity power factor but simultaneously correct the power factors of induction motors, and these are made in such sizes as to replace induction motors over a wide range of rating. There are large and small rotating and stationary apparatuses for correcting the power factor at or near individual induction motors and the like, at the plant terminals, either on the high or low sides of the transformers, at the substation and other suitable locations, and in various combinations. Why, then, is not power-factor correction universally instituted? There is the question of public relations, but this may not be so big a bugaboo as it might at first appear, and power-factor correction has been instituted in a number of cases without apparently affecting public relations. On the other hand, there may be cases where it would not pay to institute correction, as in cases of short lines with available equipment and with industrial plants connected on such systems which may have synchronous machinery and ample wiring. But old industrial plants with large numbers of underloaded induction motors and with too small wiring may cause trouble for the good installations on the system and bear losses themselves, as well as make it necessary to install power-factor-corrective equipment to maintain good voltage regulation. Manufacturers of power-factor-corrective apparatus are not in the business on a mere chance. The letter of the National Electric Light Association, of Dec. 12, 1921 to motor manufacturers, Art. 35, showed the demand for such improvements in motors and the use of static condensers, although synchronous machinery and static condensers were already on the market and being used. There must have been a reason for the demand for such equipment. In this last chapter, an attempt is made to summarize the situation and, perhaps, add further information.

112. The Power Factor as a Utilization Factor.—On the basis of lagging out-of-phase current, if any circuit carries current at 70 per cent power factor, only 70 per cent of the current in that circuit is required for energy consumption, and if it is fully loaded, 30 per cent of its capacity is tied up for magnetizing purposes. This statement holds for the utility's generating, substation, and other electrical equipment, as transformers and the transmission and distribution lines and systems, as well as the consumer's distribution system.

113. Power Factor Affects Cost.—Since the power factor is a measure of the utilization of equipment capacity, the first cost of such equipment will vary in direct proportion to the power factor. For instance, equipment bought on a 70 per cent power-factor basis will cost approximately 29 per cent more per kilowatt than if bought on the basis of 90 per cent power factor.

114. Power Factor Affects Losses.—It is well known that the copper or resistance losses on an electric system are proportional to the square of the current strength, although the monetary losses are tempered by Kelvin's law. Therefore, since the total current varies with the power factor, these resistance losses at any given power are inversely proportional to the square of the power factor, and decreasing the power factor from 100 to 70 or from 85 to 60 per cent will practically double the losses, but Kelvin's law is always to be considered. Thus low power factor makes electric service cost more, both in first cost of equipment and in operation losses.

115. Power Factor Affects Voltage.—In addition to the direct effects on cost, low power factor causes generators and transformers to give extra poor regulation, so that there are exaggerated voltage fluctuations which increase the cost of operating the system as a whole. Then too, bad voltage regulation results in severe drops just when power is most needed, causing motor troubles in the forms of somewhat reduced speeds and load capacity which affect directly the performance characteristics and the production capacity of the machinery that is driven by the motors.

Induction regulators are installed to regulate the voltage on individual distribution circuits. These regulators improve the service but do not improve the power factor. On some circuits, as where there are excessive resistance drops, regulators would be needed even if all apparatus were operated at unity power factor, but many of them could be eliminated altogether.

Any voltage at the induction-motor terminals which is less than the rated voltage for the motor causes a reduction, proportional to the square of the voltage, in its turning ability and the motor draws proportionately more current. Thus the efficiency of the motor is reduced and its coils tend to become overheated.

116. Cost of Poor Power Factor.—The power user pays the entire cost which is combined in various degrees in unnecessarily high kilovolt-ampere demand, line and copper losses, poor voltage regulation and additional electrical equipment. The first two items add to the cost of generating and distributing the energy. The third item increases the cost of rendering service and hinders the maintenance of proper manufacturing schedules. However, many find the task of power-factor cost analysis too difficult and expensive to do it thoroughly, and for that reason, most power men have let it go almost entirely. It would seem, however, since the big general phases of the question are so simple and self-evident, that it certainly is good business to improve the power factor where such improvements appear necessary. Furthermore, it would seem desirable to evaluate such improvements so as to place the burden on those who are responsible for the poor power factor and reward those who take measures to improve it. Where power-factor correction is instituted on the customers' premises by the various methods hereinbefore described, a unity-power-factor motor, a static condenser and so forth may be purchased as required or as convenient, and thus correction may be obtained gradually, along with motor substitution, as occasion arises to install a motor, until a point is reached where the power factor is satisfactory.

117. Cost of Correction.—When power factor is corrected, it requires the investment of money in equipment therefor, and like all investments, it is justified only when the fixed charges of the investment plus the extra operating expense indicate a substantial saving when compared with the reduction in costs effected by the installation of corrective equipment.

118. Benefits of Power-factor Correction.—These have been described by executives of both the utilities and industrial plants and by representatives of manufacturers of power-factor corrective apparatus. L. W. W. Morrow has treated the subject thoroughly. There may not be such good inducements for instituting correction in some cases as there are in others, but taken as a general proposition, power-factor correction is necessary, and means should be taken (as they are in some cases) by the utilities and their customers to prevent the enormous wastes due to low power factor. Authoritative estimates given in the following article tend to show that hundreds of millions of dollars of unproductive capital are invested in electric public utility properties and that much of this can be made productive by increasing the power factor. While this could not be done at once, it shows the possibilities of power-factor correction and indicates the great extent of power-factor wastes, from the standpoints both of capital and operating costs. And the power user pays the bill. It is claimed that production gains of 10 or more per cent have been made in certain cases after power-factor correction on consumer's premises and that many power users have saved 0.5 ct. per kilowatt-hour in the power bills. Further statements as to saving are given in the previous text.

119. Power Company Investment.—The following is taken from a letter to L. W. W. Morrow written by W. A. Layman[1] in response to the former's questionnaire in Chap. XIX.

"A very competent authority has subdivided a public utility's investment approximately as follows:

Table XLIII.—Subdivision of Investment

	Per Cent
Generating steam end	40
Generating electrical end	8
Transmission system	9
Substation	18
Secondary distribution system	25

"Correction anywhere else than customers' premises would fail to recover more than about 50 per cent of the capial investment involved. Economically the correction is more cheaply effected on customer's premises, therefore, provided the cost of the corrective equipment, plus its operating cost, is less than the capital cost plus operating expenses of central-station equipment of the capacity needed solely because of the low power factor. It will be found on study that the ratio of the cost of corrective equipment to the public utility's investment is surprisingly in favor of correction on customers' premises.

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[1] President, Wagner Electric Corporation.

"Howard Seelye, of the Detroit Edison Company, published in *Electrical World*, July 18, 1925, an excellent paper on the "Economics of the Distribution System."[1] On the assumption that of the investment shown for generating plant, approximately one-quarter only represents the electrical generating plant as distinguished from steam and building investment, the division of total investment of a central-station plant will show the following:

TABLE XLIV.—TOTAL ELECTRICAL INVESTMENT

	Total investment	Per cent of total in electrical investment	Per cent of total brought to unity
Miscellaneous	20		
Generating plant	32.5	8	14.4
Transmission system	9	9	16.3
Substations	12.5	12.5	22.5
Secondary distribution system	26	26	46.8
Total	100	55.5	100

"Therefore, it will be clearly seen that power-factor correction beginning in the substation is at best reclaiming only 53 per cent of the electrical investment for equipment, and is accomplished entirely by an increase of public utility's investment of a large amount, and with substantial operating losses added and assumed by the utility itself.

"When correction is made on the customer's premises, the capital investment is carried by the consumer responsible for the low power factor, and neither capital investment nor increased distribution losses are put on the shoulders of the public utility itself, nor on the consumers as a class.

"According to statistics issued from the national office of the National Electric Light Association, the total capital investment of electric public utilities in 1924 was $6,600,000,000 with operation kilovolt-amperes of 22,158,000. In open figures, therefore, the total existing central-station capacity in the United States has a capital value of approximately $300 per kilovolt-ampere. Hence, the average electrical investment of the public utility company is approximately $165 per kilovolt-ampere.

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[1] See Index.

"What the public utilities can do, therefore, by power-factor correction is to reclaim $165 capital investment for each kilovolt-ampere saved by such correction. If temporizing partial correction at substations is the policy adopted, then the capital recovery by such correction will be only 53 per cent of $165 or $87.50 per kilovolt-ampere recovered, and as stated above, 47 per cent of this $165 will not be affected by power-factor correction at substations; whereas if complete correction on the customer's premises is the policy adopted, the capital recovered by the public utility through such correction will be $165 for each kilovolt-ampere so recovered. It seems to me that these figures just stated give the final answer to your question 7, as to where correction should be effected.

"Views differ widely as to the necessity for power-factor correction. Such difference in points of view is hard to understand in face of figures produced by simple analysis. Views differ widely though more naturally as to the policy to be pursued in quickly effecting some kind of relief, and substation correction is frequently advocated as a quick way of correcting power factor. It is, of course, quick but relatively expensive from every angle of consideration. The above showing alone, which by no means represents all the advantages to the public utility to be derived from correction, assuredly justifies correction at the source, namely, the customer's premises.

"Whether substation correction is the only quick way to secure relief is quite open to question. It has been demonstrated by one large public utility company that a rate schedule equitably applying proper charges for both services rendered will very quickly effect power-factor correction on the customer's premises, and that public service commissions give their whole-hearted approval of such rate schedules when the logical principles behind the rate schedules proposed are made clear to them.

"12. It is beyond question that it is not only wise management policy, but also in the interest of equitable service to the public, for every utility to make power-factor correction one of its aggressive activities, and in the writer's opinion we are not far away from the time when power-factor correction will be required by public utility commissions as one of the most obvious ways for the reduction of cost of the electric current to the public at large.

"The N. E. L. A. statistics show that the gross revenue in 1924 of all the electric public utilities of the United States was $1,350,000,000 with a capital investment of $6,600,000,000 or a capital investment of $5 for each dollar of gross revenue. Of this $5 of capital investment, according to Mr. Seelye's figures above quoted, 55.5 per cent or $2.78 is invested in electrical equipment. There have been widely varying opinions as to what proportion of this electrical investment, $2.78 per dollar of gross revenue, is unproductive capital investment because of low power factor. If the average power factor of the country as a whole is 75 per cent, then 25 per cent of this electrical investment is unproductive, or approximately 70 cts. per dollar of annual gross revenue. It is the writer's personal opinion that 70 cts. is too low and that in general terms it may be stated that the capital investment idle because of low power factor is equal to the total gross annual revenues of all the electric public utilities of the country. Or, in other words, that the electrical equipment unproductive is $1 for every dollar of gross annual revenue. If these figures are even approximately correct, it is certain that the public utility commissions will shortly require operating policies which will make this $1 of electrical equipment productive."

120. Further Excerpts from Writings of W. A. Layman.—"The three deterrent factors at the present moment are:

"*A.* Correction of power factor through rate schedules inevitably involves a reduction of revenues. It is impractical from the viewpoint of public utility executives to introduce power-factor schedules which increase the cost of service to the power user. Therefore, we may not expect power-factor rate inducements until (1) general revenues permit a scaling down of income, or (2) service conditions make power-factor correction imperatively unavoidable, or (3) increasing loads require increasing plant and distribution capacity, in which event capacity can be wisely secured through power-factor correction and financial concessions for the purpose of such correction.

"There is no question but that chief executives of the utility companies today understand all the serious aspects of the power-factor problem—financial, service, etc.—but putting ourselves in their places, the herein outlined procedure is what we would do.

"*B*. Subordinate commercial executives of the public utilities are just as human as salesmen in apparatus fields. They will not tackle a hard job, such as introducing power-factor rate schedules would be from their own point of view, until ordered to do so by the higher executives of their companies. Sooner or later this will come, and in the meantime our organization can usefully prepare the way by familiarizing the commercial executives in every reasonable way with the aspects of the problem, so that in due season they will understand it technically as well as commercially. Personally, I do not believe that the problem of explaining magnetizing current to the power user is anywhere nearly so difficult as commercial executives now paint it.

"*C*. There is a real element of difficulty in the meter situation, and the meter companies have not arisen to the opportunity ahead. The real offender is the very small power user. Effective power-factor correction will not occur until a practical plan is devised for metering in some simple manner (or its equivalent) the real operating conditions of the small consumer's installation.

"This picture of the situation, on first blush, does not sound very promising for power-factor correction. My personal view, however, is that there is one factor which largely removes the gloom from this picture, namely, production volume for all the stations is increasing so rapidly that revenues increasing more rapidly than costs will soon make necessary downward revision of rate schedules.

"Some of the commercial men are complaining about what they regard as the conservative policy of many utility executives in devising practical measures to secure power-factor correction. My personal answer to this complaint is that the conservatism is much more apparent than real. The stage setting is not right, for the reasons above enumerated, where this conservatism is being displayed. I have yet to discuss power factor with the public utility executive official who does not disclose fully and frankly both a knowledge of the problem in all its important aspects and a desire to accelerate correction. They are all in the business, however, of making a proper return on their invested capital, and most of them are in the position of a manufacturer with a plant full of obsolete, or partially obsolete, machinery, together with a gross income that about covers dividend requirements. All the obsolete tools cannot be scrapped at once. There is a delicate balance between the rate of modernization of plant and the enlargement of net income. Any manufacturer will accelerate as rapidly as possible the modernization of his equipment as earnings permit. Only a tragedy in his situation would permit an abnormally rapid modernization of plant at the cost of a sharp reduction of net income available for the payment of dividends when there has been a continuous, unbroken record of dividend payments.

"One central-station executive, states he has no power-factor problem because his peak power factor is somewhere between 80 and 90 per cent. Yet we have seen his switchboard meters measuring 60 per cent power factor on the total load, and the magnetizing current for the system is so large as sometimes to require the operation of two large generators to supply this energyless load.

"It is astonishing how low operating power factors are in some cases. You would hardly believe it possible that instances such as the following could exist: On a southwestern distribution system there are three feeders running out of a certain substation to supply oil-well operations. There are graphic-recording power-factor meters on each of these feeders, and the three feeders showed, under operating load conditions 65, 35, and 20 per cent power factor, respectively. We had just installed a few corrective motors in the 65 per cent feeder, and prior to the installation of these the power factor of this feeder was down with the other two."

The following excerpts from the letter to L. W. W. Morrow, above referred to, are interesting and instructive:

"Your questionnaire is primarily directed to central-station men. Our comments and conclusions with respect to each of your questions can be based only upon our own experience through contact with central-station executives.

"The natural presumption might be that our views on power-factor correction, as a general problem, can hardly be expected to square with the best central-station practice in power-factor correction from the utility executives' point of view, because our interest is the sale of a corrective device. It so happens, however, that this problem is unique in this respect: so far as our studies of the power-factor problem go, the policy of the public utility which most effectively and ecnomically operates to power-factor correction, at the same time operates to our greatest commercial advantage as the distributor of a manufactured corrective device. In other words, the writer has not been able to see, up to the present time, any conflicting of purpose between the public utility and ourselves in preventing the economic waste due to low power factor. We must concede that there is, at the present time, an occasional conflict in point of view between ourselves and some central-station executives, but this arises not so much from a conflict of inherent principle as a temporizing policy with the power-factor situation. For example, we meet with the occasional assertions:

"*a.* The utility has no power-factor problem.

"*b.* The correction of power factor is a consideration quite secondary to other and more important phases of operation and, therefore, a negligible matter for the time being.

"*c.* It suffices for the present to introduce corrective apparatus at the utility company's general expense at centers of distribution, and correction on the customer's premises is relatively insignificant in importance.

"*d.* Excess capacity at the power house is alway necessary under all conditions and, therefore, the power factor of the load is unimportant, particularly if corrected at the company's expense by some means at the power house, or if ample generator capacity is there available. The public cannot be made to understand what power factor means, and, therefore, power-factor correction should be indefinitely postponed on that account.

"*e.* There has been unwarranted and gross exaggeration in the magnitude of idle or excess investment growing out of low power factor; the actual facts do not justify attaching importance to power-factor correction as a medium toward more effective capital investment.

"These and other comments do not represent the intrinsic facts of the situation. Other executives go to the other extreme in a frank confession:

"*f.* Their power-factor condition is a very serious one, and pressing for an immediate correction.

"*g.* Interchange of power on a large scale cannot be satisfactorily effected with power factor running riot and the magnetizing current capable of being passed from one end to another.

"*h.* The customer responsible for the low-power-factor load should not be given at the same price, two services as against one service to the customer whose load is of high power factor. (By two services is meant the supplying of 'energy' and 'magnetizing' current in the one instance, as against 'energy' alone in the other instance.)

"*i.* The next important change in the establishment of operating principles is a rate differential between the high-power-factor and the low-power-factor customer, *i.e.*, the making of rate schedules in such form that every class of customer pays for the service he receives so nearly as it may be reasonably determined —a policy which is at the present time not attempted by a large number of public utility companies.

"*j.* If the inequality of service charges at present existing between the high-power-factor and the low-power-factor customers is not voluntarily corrected by the public utility itself, the time is not far distant when its correction will be enforced by the regulating public service commission.

"Proceeding now to the consideration of your questions in their order, our experience suggests the following remarks:

"1. We are convinced that a rate clause is essential. We have attempted in various localities to sell Fynn-Weischel motors in close cooperation with public utility executives on the 'performance characteristics' of the motor aside from power-factor correction, that is to say, to sell it at its higher price without return on account of its higher economies. We have met with some success in this effort, but frankly confess that results come but slowly, and the Fynn-Weischel motor, or any other power-factor-correcting device, cannot be broadly sold without a rate schedule which gives the customer a financial return on the added initial investment, which such corrective aparatus inevitably involves.

"2. From the standpoint of our personal interest, we favor a power-factor clause based upon the average monthly power factor, such for example, as will be recorded by an integrating reactive kilovolt-ampere meter. As the most equitable basis from an economic point of view, however, we think a demand rate which takes power factor into account is preferable.

"3. Our study of this situation prompts us to favor system with neither penalty or bonus as such, but rather a service charge system, pure and simple, which frankly states that the company is prepared to supply two kinds of service—'energy' and 'magnetizing' current. It should be a rate system which in its make-up practically recognizes both the energy service and the magnetizing service in their proper proportions.

"The company has both kinds of service to sell and its rate schedule should provide for either in any amount the customer requires for any purposes, for which they are separately or jointly needed. There can be no justification of the policy which permits a customer to take any amount of magnetizing service his operations require, such service to be paid for by distribution over the community as a whole, a general tax in the making up of community rates.

"4. This question is answered in our reply to question 3. If the rate system makes a proper charge for each kind of service rendered, there would be no discrimination in contract forms between classes of users.

"5. It may be quite desirable for small users (10 or 20 hp.) to have a rate schedule involving a simple kilovolt-ampere-hour measurement, such as the well known Sangamo ampere-hour meter or its equivalent; for somewhat larger loads (20 to 50 hp.), a watt-hour meter with a kilovolt-ampere demand attachment or the Wright demand meter, and a two-part rate covering the use of the demand for a specified minimum monthly period and a suitable energy charge for the excess; for still larger loads (50 hp. and larger), a two-meter (active and reactive) arrangement or a graphic instrument, according to circumstances."

121. Costs and Rates.—Based on the 1924 figures given in Art. 119, with the gross revenue of all the public utilities of the United States at $1,350,000,000, with a capital investment of $6,600,000,000, and with 55.5 per cent, or $3,663,000,000 invested in electrical equipment, Table XLV shows the amount of idle invested capital in terms of various assumed power factors, whether or not power factor is responsible for said idle capital, for the country as a whole. These figures do not include the idle capital investment of isolated plants.

Table XLV shows that, regardless of the exact figures for the power factor and the capital necessarily tied up for other purposes, the total idle invested capital is enormous.

The power user, however, pays for all power-factor wastes of the utilities, besides his own losses on his own premises due to whatever causes.

On the authority of Charles J. Russell (Art. 36), power-factor correction is the one major economic opportunity remaining in the electric light and power industry. The statements of others are given throughout the text, and from a careful study of the general proposition, it would seem that there is much need for power-factor correction and that the power user is the goat through his own fault in demanding so much magnetizing current for which he should justly pay.

TABLE XLV.—POWER FACTOR AND IDLE INVESTED CAPITAL

Power factor	Idle invested capital	Number of unproductive dollars per dollar of annual gross revenue
60	$1,465,000,000	1.085
65	1,292,000,000	0.954
70	1,000,000,000	0.822
75	916,000,000	0.678
80	732,000,000	0.542
85	550,000,000	0.411
90	366,000,000	0.271

Costs due to low power factor are both direct and indirect, and are borne either by the utility and passed on to the consumer, or directly by the latter. Capital costs due to the expensive apparatus required to maintain the voltage at the consumers' meters, as well as the increased losses in its lines, distribution system, and electrical equipment, are the direct costs to the utility caused by the consumers' low power factors. The direct costs to the consumers are the capital cost of the necessary larger wiring and the operating cost due to heat losses in plant distribution systems. The indirect cost to the utility is the increased difficulty of operation, and in some cases, good service is rendered impossible with a resulting loss of goodwill. The indirect cost to the consumer is chargeable to all those effects previously mentioned in the text.

If all power users had unity power factors, there would be no power-factor wastes due to their equipment.

While it is known that rates for service follow costs and, therefore, will always be comparable with the cost of operating isolated plants, it cannot always be foretold whether rates will go up or down in the event of rate readjustment, but if the rates go up, the plant with a poor power factor will ultimately bear the increase, while if the rates go down, the plant with a good power factor will ultimately secure the benefit. The isolated plant is no small factor, as mentioned in Art. 30.

One chief engineer of a public service commission stated to the author-editor that in his opinion power rates would not go down although lighting rates would be reduced, and that bonuses should be given for and above certain high power factors, but that penalties should increase sharply below such limits. A utility executive stated that power-factor penalties would be instituted on that system, but just how or when he could not say. Some of the power users had very bad power factors and yet the utility had made money right along. A utility engineer said that whenever he found a large customer's power factor coming down, he showed the customer how to correct it. Probably these and other conditions are very common.

122. Estimating The Approximate Energy Loss in a Distribution System.—In a letter dated Aug. 1, 1925, H. Weichsel writes as follows:

> In order to estimate the approximate energy loss in a distribution system, the following procedure is recommended:
>
> Measure the voltage on the terminals of the supply transformer and measure the voltage on the ends of the distribution system. The difference between these two readings gives an apparent voltage drop. The real voltage drop, however, is larger than this value and is obtainable by dividing the measured voltage drop by the power factor of the system, as shown by the following:

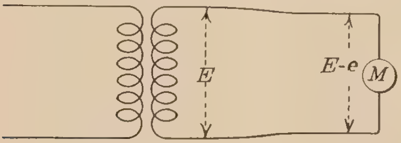

FIG. 113.—Method of making voltage measurements.

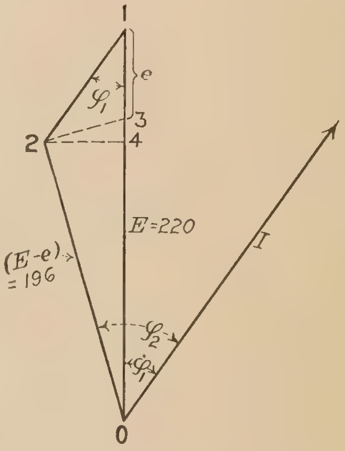

FIG. 114.—Vector diagram for the conditions of the example.

> If I is the current taken by the motor and 0–1 is the voltage on the terminals of the transformers, and 0–2 is the voltage on the terminals of the motor, then the voltage drop measured in the manner outlined above would be the value 1–3, but this is very nearly the same as the value 1–4, where 2–4 is vertical to 1–0. The actual ohmic drop in the

distribution system is 1–2, and as angle 2–1–0 is equal to angle φ_1, it follows that 1–2 is equal to $\frac{1\text{–}4}{\cos\varphi}$, which is very nearly equal to the measured drop divided by the power factor.

"The energy loss in the distribution system is given by the equation:

$$I^2r = I(Ir) = I\frac{e}{\cos\varphi}.$$

"The input to the system is given by the relation:

$$I.E \times \cos\varphi.$$

"Therefore, the energy loss in the distribution system expressed in per cent of the input to the system is given by:

$$\frac{Ie}{\cos\varphi\, IE \cos\varphi} = \frac{e}{E}\,\frac{1}{\cos\varphi^2}$$

which shows immediately that the percentage loss in the distribution system varies inversely with the square of the power factor.

"In a similar manner, the copper loss in the distribution system could also be expressed in per cent of the input to the motor. In order to do this, we simply transform the mathematical operations as above but substitute the input to the motor in place of the input to the whole system. In order to obtain a simple relation, we must call the input to the motor equal to the voltage 0–2 × cos φ_1, instead of cos φ_2, which produces an error which is naturally very small.

"An example will show how large these distribution losses may be. In an actual installation, the drop was measured to be 12.3 per cent of the voltage across the motor and the power factor on the system was 65 per cent. The copper loss in the distribution system expressed in per cent of the motor input, therefore, was $\frac{12.3}{(0.65)^2} = 29$ per cent. If we express the loss in per cent of the input to the system, we obtain:

$$\frac{\text{Measured voltage drop}}{\text{Transformer voltage}} = \frac{24}{220} = 10.9 \text{ per cent of voltage input.}$$

With 65 per cent power factor, this would correspond to $\frac{10.9}{(0.65)^2} =$ 25.5 per cent of the energy input to the system.

H. Weichsel

123. Where Synchronous Motors and Static Condensers are Used Together.—In one form of 100-kva. induction furnace, a crucible is surrounded with a suitably cooled coil of copper having a radius greater than that of the crucible. The generator end of a 750-kva. motor-generator set supplied the current in the copper coils of the induction furnace at a frequency of about 480 cycles per second, with a power factor of about 13.5 per cent. The motor of the motor-generator set is of the synchronous type. Because of the low power factor of the induction furnaces, static condensers are employed on the generator side to correct the power factor to about 80 per cent.

124. Power-factor Correction and Load Conditions.—There are certain phases of the power-factor situation that depend upon light or no-load conditions. For instance, lightly loaded transformers have low power factors. This occurs chiefly at night, and over Sundays and holidays, in industrial plants. Thus, where the power factor is averaged over an entire month, peak loads in industrial plants may make the power factor good while such loads are on, but the transformers will reduce the average power factor for the month to some extent, thus causing a loss to the power user receiving a bonus. Again, when power-factor-corrective apparatus is left connected across plant terminals during light or no-load periods, such apparatus tends to make the power factor very high or leading, thus causing a loss to the utility paying a bonus. That is why meters have to be ratcheted so that they cannot run backwards (Art. 61).

Raising Power Factor Covers Loss of Generator.[1]—About three years ago the Penn Central Light & Power Company, Altoona, Pa., was placed in an embarrassing predicament by the loss of a 5,000-kw. generating unit in the Williamsburg plant. The new Saxton plant was not in operation, and since all generating equipment was needed to carry the load, it seemed that curtailment of service would be necessary. All customers having synchronous motor equipment, however, were asked to over-excite their motors. This request was made by telephone in less than two hours, and the system power factor was raised from 78 to 84. This represented a reduction of more than 3,000 kva. in line losses and permitted the carrying of all the load with good voltage regulation during the temporary emergency.

It would appear probable that if careful investigations were made as to cyclic demands from certain classes of machines the proper use of fly-wheels would permit the use of smaller motors, just as the energy stored in the fly-wheels of small power presses helps to operate the heavy presses belted to the common line shaft, As an example, in a case where a 15-hp. induction motor could not accelerate the fly-wheel of a large press which it could satisfactorily operate after it once was started, the 7-in belt was removed, a 5-hp. induction motor was substituted for the 15-hp. motor, a 1-

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[1] *Elec. World*, vol. 86, p. 1211, 1921.

in. belt was substituted for the 7-in. belt, and the 5-hp. motor then accelerated and operated the large press with no further trouble.

125. Public Relations.—Public utility history may be said to consist of pioneering, engineering, commercial, and public relations. Activities in public relations have been prominent for about ten years, being based upon the fundamental principle that a successful trade must be of advantage to both parties concerned. This is one of the reasons why charges for service must often be based on the consideration that steam boilers, an engine, and perhaps an electric generator are available by the manufacturer using purchased power.

> The immense increase in the use of our energy by industries which hitherto have produced their own electric power and could continue to do so has taught us the value of service to these industrial customers. They would not use it unless it paid them to use it. We have also learned the value of that industrial business to our non-industrial customers, who have profited by the reduction of our costs through the increased output which the industrial sales have made possible.[1]

L. R. Nash[2] states in his recent book[3] from which the following excerpts are taken:

> It is of the greatest importance that there should be public appreciation of the mutuality of interest between public utilities and the communities service. The old attitude of antagonism still survives in too many cases, fostered by political or personal interests or failure to understand the fundamental principles which now control public utility service. It has been pointed out that a public utility is a public servant, and that it works for a fixed wage or at least one variable within quite narrow limits, the real profits from its operations and development accruing to the communities served through reduction in rates and improved service.
>
> The general public should understand that public utilities stand ready to furnish any range or character of service within the scope of their authorizations which their patrons are willing to pay for, but that a few prospective patrons should not call for exceptional expenditures or abnormal service costs at the expense of existing patrons unless the latter are willing to assume the burden. Nor should the patrons of a public utility assume obligations which have no relation to the service which they receive.

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[1] See Art. 32.

[2] Public Utility Engineer, Stone and Webster, Inc.

[3] "Economics of Public Utilities," New York, 1925.

The public should also be brought to understand that the fundamental purpose of regulation is so to adjust the operations and rates of public utilities as to give satisfactory service to patrons and a fair return to the investors in the properties. It follows that the public utilities, although naturally monopolistic in their operations, are deprived of opportunity otherwise offered in the absence of competition to secure excessive incomes, at least if their customers or the commissions having jurisdiction are sufficiently interested to take the necessary preventive steps. Such steps have, in fact, been taken freely, with the result that the returns earned by public utilities are, in general, substantially lower, although more stable, than those found in competitive industries. Regulation has decreased rates where they were too high and increased them where they were too low, in each case consistently with the cost of the service rendered.

Public utilities are also seeing the wisdom of complete avoidance of political affiliations and entanglements. When it is remembered that the public is being served at cost, the occasion for special favors from public officials disappears, and every official and employee of a public utility should be free to act and vote on political issues in any way he pleases.

It is interesting to note in Table XLI that thirteen of the answers to Mr. Morrow's questionnaire state that power-factor correction did not affect public relations, while two stated that it did.

An editorial in *Electrical World*,[1] stated:

Investigation by a number of central-station companies to determine the status of their public relations has revealed that comparatively few people are hostile to the utilities. A big majority—95 per cent of the customers of one company—are satisfied with existing rates, service, and so on, and are classified as mildly favorable or neutral. Some are even enthusiastic supporters of their utilities. Thus, if there ever was hostility toward electric public utilities in general, it would appear that the public attitude toward them has changed from a state of passive resistance to one of favorable neutrality bordering on friendliness. This is an accomplishment, and utility executives are to be commended for their determination to employ every legitimate means of making still closer friends of the public.

126. L. R. Nash on Power Factor.—The following is taken from the book referred to in Art. 125.

Much has been written about power factor from engineering and commercial viewpoints, but the seriousness of the problem has not been appreciated by the average utility executive who looks upon low power factor as one of the burdens of the business which, although involving large capital expenditures and appreciable operating costs, cannot be avoided.

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[1] Executives and Public Relations, *Elec. World*, vol. 86, p. 1039, 1925.

It has been pointed out that low power factor is caused by wattless current used for magnetizing motors and other service facilities. This wattless current passes through the customers' watt-hour meters without registration. A customer using synchronous motors provides his own magnetizing current from a separate exciter, the power for which is registered on his meter and, therefore, paid for. By simple adjustments of excitation, the power factor of such motors may be brought up to unity or made "leading" to correct for "lagging" conditions elsewhere. There is an obvious discrimination in furnishing magnetizing current free to one customer and requiring another customer to pay for it. This discrimination may be avoided through rate differentials, but it is by no means clear that this is the best solution of the problem from an economic viewpoint.

The average power customer has no conception of the meaning of power factor and its effect upon service costs. He resents a penalty for low power factor because it represents an intangible something over which he thinks he has no control. As a matter of fact, customer power factor may be increased within wide limits through careful fitting of motor capacity to work required and other adjustments that not only involve no material cost to the customer but tends to reduce his equipment cost. It may further be controlled by special types of motors, rotary or static condensers, and other means that do not involve added investment. The customer naturally will not assume such investment unless he sees compensating advantages.

The extent to which customers should be called upon to invest in power-factor-correction devices in order that the electric company furnishing the power may curtail its otherwise necessary investment is an engineering problem that has so far been solved in only a few special cases. Studies which the author has made indicate that a power company may reduce its charges for high-power-factor service below those for low-power-factor service to a sufficient extent more than to offset the carrying charges on the customer's additional investment and still show a saving for itself through reduction in investment necessary to serve such a customer and through lower operating cost.

There are other ways of bringing about the same result than through rate adjustments. If a customer objected to making the additional investment necessary to secure high power factor, the power company might advance the excess of such cost over that of the more common low-power-factor equipment which the motor salesmen are apt to offer, the advance being recovered through instalment payments or through witholding for a suitable period a reduction in demand charge to which the customer would otherwise be entitled because of his high power factor. These or any other methods of power-factor correction assume that it is cheaper to furnish magnetizing current on the customer's premises than it is to produce it at the central station and deliver it to the customer, as has been generally done in the past.

Utility executives who have given this matter careful thought are of the opinion that it is one of the most important problems which the electric industry has to solve. It requires further careful engineering study to determine the relative cost under different circumstances of furnishing magnetizing power at the source of power and the point of utilization. There is need also of further education of customers regarding power factor and its effect upon service cost and the methods whereby power factor may be increased with attendant reduction in cost of service.

The author urges upon the electric industry an exhaustive study of all phases of the power-factor problem with a view to working out a program under which the total combined investment in power production and utilization facilities may be reduced. This would, of course, mean a reduction in the total cost of power service.

127. A Possible Solution.—Power factor has a very distorting effect upon the judgment of many people who are dealing with it, as well as on the motors and circuits. Some have experience with one set of conditions, while others have very confused notions of what power factor is in many cases and are apt to draw wrong conclusions. It is much more important to give a discriminating presentation of the situation as a whole, as well as the various viewpoints from many sides, than to some particular feature of the situation, and this has been the aim throughout the text. There may be cases where the magnetizing current may be more cheaply produced by the central-station generators, and there are other cases where it cannot thus be more cheaply produced. Likewise, there may be cases where the power factor is of lesser importance than other existing features, and there are other cases where it is of the utmost importance. In all cases, situations must be analyzed and the necessary steps taken. But it should be remembered that the power user is chiefly responsible for low power factor through the demand for magnetizing current made upon the utility without notice by his induction motors.

It does not appear that the best results can always be obtained by the location of power-factor-corrective apparatus at the substation, although undoubtedly the quickest results are thus obtained in the absence of financial inducements to cause power users to institute correction on their premises. It would appear that the eventual place to institute power-factor correction is on the customers' premises where the demand for it is made. One gathers this impression from the National Electric Light Association's letter in Art. 35, which seems to strike right at the heart of the situation.

With the electric utility companies constantly installing synchronous machinery at various locations for increasing the power factor back to the generating station and improving voltage regulation, even if old generators are used as synchronous condensers in many cases, and with the manufacturers of corrective apparatus and special motors educating both the utility and industrial-plant executives as to the benefits of correction in various manners, it would appear that rate schedules which will speak for themselves as to the value of power-factor correction and the necessary metering equipment eventually will arrive.

It would seem that the logical method is for the utilities to start with the larger power users through financial inducements for good power factors and gradually work down to the smaller consumers, while manufacturers of power-factor-corrective apparatus can gradually install such devices on customers' premises, either directly or through contractors, with the moral encouragement, at least, of the customers' use of such apparatus by the utilities. Eventually, the parties working toward a common goal should meet. This program would be greatly accelerated if the utilities, either of their own accord or through measures taken by the public service commissions, should act to make more of the idle electrical capital investment productive.

In France there is legal recognition of power-factor control; in Germany tariffs carrying increased rates for low power factor have been generally adopted and in England the passage, upon memorialization, of an Act legalizing a kva. basis for the demand charge.

128. Some Industrial Loads.—In line with the policy of keeping the electrical industry informed regarding the latest developments in its field and the present status of its activities, the *Electrical World*, at the opening of the year 1925, instituted a survey of the industrial plants of the country to ascertain the present use of electric energy for industrial purposes. The

United States Census Bureau has cooperated in a liberal manner, and these government tabulations, taken in conjunction with the above survey, have furnished a most reliable basis for estimating the present industrial load of the sixteen fundamental industries of the country as grouped by the United States Census Bureau, as follows:

TABLE XLVI.—CLASSIFICATION OF INDUSTRIES

1. Chemicals and allied products.
2. Food and kindred products.
3. Iron and steel and their products, not including machinery.
4. Leather and its finished products.
5. Lumber and allied products.
6. Machinery.
7. Metals and metal products other than iron and steel.
8. Musical instruments and phonographs.
9. Paper and printing.
10. Railroad repair shops.
11. Rubber products.
12. Stone, clay, and glass products.
13. Textiles and their products.
14. Tobacco products.
15. Transportation equipment, air, land, and water.
16. Miscellaneous industries.

The above numbers have been placed before the various industries in the order in which they occur in the tables.[1]

Only the totals for the various sections are herein tabulated, but they are shown for all industries in the groups of states in the above mentioned tables, and the *Electric World* has more detailed information in pamphlet form.

The data in Table XLVII show that there is still much to be done in electrifying the industries and that the electric energy generated in private plants is equal to 60 per cent of that purchased from central stations for industrial consumption; so much of the country's magnetizing current is generated on the power user's premises after all, though it may not be kept out of his distribution system. It is believed that a very large field for power-factor-corrective apparatus will be found in the private generating plants.

129. Influence of Cheap Power on National Prosperity.—C. M. Ripley, General Electric Company, Schenectady, N. Y., made the following statements in an address[1] delivered before a number of assemblies.

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[1] *Elec. World*, vol. 86, pp. 512, 744 and 1002, and 1256, 1925; and vol. 87, Jan. 2, 1926.

> The importance of efficient power plants upon the general prosperity of the country is illuminatingly shown by the train of gears in the illustration.
>
> The manufacturing companies design, build, and sell apparatus that is efficient. Because the power plants do use the latest electrical apparatus, they are able to generate power at a low cost. Low electrical rates encourage the factories to use more power. This, combined with automatic machinery, makes the factory more efficient and permits a greater output.

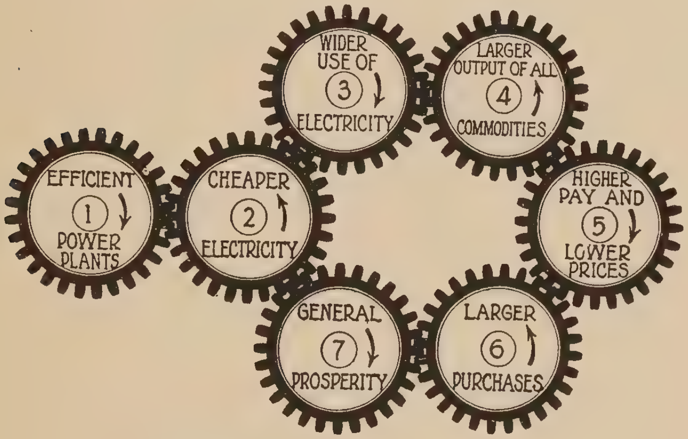
WIDER USE OF ③ ELECTRICITY
LARGER OUTPUT OF ALL ④ COMMODITIES
EFFICIENT ① POWER PLANTS
CHEAPER ② ELECTRICITY
HIGHER PAY AND ⑤ LOWER PRICES
GENERAL ⑦ PROSPERITY
LARGER ⑥ PURCHASES

Fig. 115.—The gear train of industry.

> Because of the greater output, it has been possible to adopt the eight-hour day and to pay higher wages, at the same time selling the product at a lower unit price. As a consequence people have more money to spend and they are able to buy more of the necessities and luxuries of life, as indicated by wheel 6. The greater consumption of goods creates prosperity for all.
>
> The improvement in machine efficiency has had its effect upon the comparative output of factories. For example, a factory equipped in 1900 cannot compete with a factory fitted with modern machinery. The company that fails to discard the out-of-date and install the latest mechanical improvement is likely to become bankrupt for the reason that the alert and thoroughly modern competitor can reduce prices below the cost of the less progressive firm.

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[1] *Power*, vol. 61, p. 848, 1925.

TABLE XLVII.—DISTRIBUTION OF THE INDUSTRIAL LOAD IN THE UNITED STATES, AS OF JAN. 1, 1924, AND ENERGY CONSUMED BY INDUSTRIAL PLANTS DURING 1924

	United States	New England	Middle Atlantic states	South Atlantic states	North central states	South central states	Mountain and Pacific states
Primary horsepower owned by establishments reporting:							
Steam engines (not turbines)	13,386,996	1,284,656	4,246,432	1,250,636	4,150,814	1,528,697	925,761
Steam turbines	3,340,204	493,157	1,028,077	235,156	1,207,217	195,998	180,599
Internal-combustion engines	1,254,140	46,933	400,646	113,603	535,780	106,080	51,098
Water turbines	1,803,317	761,211	388,510	258,558	312,022	23,712	59,304
Electric motors run by purchased energy, horsepower	13,359,096	1,564,728	3,530,168	1,325,983	4,613,377	876,464	1,447,925
Total primary horsepower	33,143,753	4,151,136	9,593,833	3,183,936	10,819,210	2,730,951	2,664,687
Electric motors run by energy generated in private plants, horsepower	8,888,569	1,102,423	3,068,554	655,719	3,336,472	347,203	378,198
Boilers:							
Number	60,192	6,118	18,211	6,356	18,755	7,968	2,784
Horsepower	16,069,113	1,483,620	5,394,650	1,382,790	5,418,796	1,654,926	734,331
Number of companies having private electric generating plants	8,157	1,038	2,456	704	2,816	754	389
Estimated rating of prime movers used in private generating plants, horsepower	6,416,763	845,805	2,182,000	483,514	2,311,227	310,413	283,804
Estimated electrification of the industry, per cent.	59.7	58.2	59.6	56.8	64.0	43.2	65.0
Energy consumed, kilowatt-hours:							
Purchased from central stations	19,393,722,000	1,807,222,000	6,586,337,000	1,399,178,000	6,151,506,000	1,386,567,000	2,042,912,000
Generated in private plants	11,630,761,000	1,285,975,000	3,915,171,000	740,475,000	4,501,535,000	651,665,000	535,940,000
Total energy consumed	31,004,483,000	3,093,197,000	10,501,508,000	2,139,653,000	10,653,041,000	2,038,232,000	2,578,852,000

Generators in private plants:							
Rating of a-c generators, kilovolt-amperes	4,411,577	628,706	1,511,375	382,430	1,498,988	173,210	216,868
Rating of d-c generators, kilowatts	1,501,835	122,859	510,675	65,486	642,613	114,178	46,074
Total rating of generators, kilovolt-amperes	5,913,462	751,535	2,022,050	447,916	2,141,601	287,388	262,942
A-c motors:							
Number	1,176,439	266,340	251,923	119,540	407,138	43,718	87,780
Horsepower	15,389,566	2,273,626	4,122,420	1,544,834	5,134,609	888,684	1,424,942
D-c motors:							
Number	668,298	56,892	223,145	34,630	262,478	52,935	38,218
Horsepower	6,858,099	393,525	2,476,302	436,868	2,815,240	334,983	401,181
Total motors:							
Number	1,844,737	323,232	475,068	154,170	669,616	96,653	125,998
Horsepower	22,247,665	2,667,151	6,598,722	1,981,702	7,949,849	1,223,667	1,826,123
Motors under 5 hp.:							
Number	989,010	206,480	246,227	73,983	343,339	57,484	61,497
Horsepower	2,266,441	403,802	592,570	167,459	796,654	116,812	189,144
Industrial electric heating:							
Average monthly load during 1924, kilowatts		37,531	This is destined to be a great industrial load in the future. The surface has scarcely been scratched. Overall costs often favor electric heat over the usual fuels. See Chap. XVI				
Energy consumed during 1924, kilowatt-hours		21,712,300					
Motors (horsepower):							
A-c, per cent	69.2	85.3	62.5	78.0	64.6	72.6	78.0
D-c, per cent	30.8	14.7	37.5	12.0	35.4	17.4	22.0
Under 5 hp., per cent	10.2	15.1	9.0	8.5	10.0	9.6	10.4
Energy supplied by central stations, per cent	62.5	58.4	62.7	65.4	57.7	68.1	79.2
Energy generated in private plants, per cent	37.5	41.6	37.3	34.6	42.3	31.9	20.8

What is true of firms is also true of nations. People in Europe and Asia use less power and the people have less to spend, less to wear, and less to eat. A British economist says that the American workman has three times the prosperity possessed by the Briton.

Going still further away, witness the rickshaw runners of China and Japan; the men threshing corn and wheat by hand in Egypt and India; those who excavate earth and rocks and carry out the material in baskets, or those in Egypt who lift water in baskets for irrigating purposes.

Compare their pay and their standard of living with that of Americans who use steam and electric shovels, steam and electric pumps, steam and electric cranes, gasoline automobiles, kerosene tractors, and modern machinery in factories, mills, and mines.

Wherever you see high wages, there you find power-driven machinery; and wherever you find no power-driven machinery, there you find low wages.

Large factory pay envelopes do not depend on a generous employer. The eight-hour day does not depend on a kind-hearted boss. What is the main determining factor? It is power and modern machinery.

The man engaged in the power industry is doing his part, not only to increase general prosperity, but to provide mechanical means for lifting loads, carrying burdens, and turning wheels that formerly had been lifted, carried, and turned by human muscles.

He is helping to emancipate the race from dull drudgery, and he is helping to elevate labor to a higher standard of dignity and a higher standard of living.

F. G. Baum[1] states the case as follows:

There is a steady increase in the horsepower placed back of each worker, there being 29,000,000 hp. to 9,000,000 workers, or a ratio of 3.24 in 1919, the ratio being 2.14 in 1899 and 2.82 in 1900. This increase of power per worker means, of course, increased output per worker, and this means reduced cost of product and larger wages paid to the workers. In terms of energy, a man can do only about 1 kw.-hr. per day of eight hours, requiring eight men per horsepower for one eight-hour shift. The cost of this labor would, at present wages of, say, $4 per day per man, be $32 per eight hours per horsepower. But this power can be supplied electrically or mechanically for a few cents per day. Hence, the cause of the low production cost and the increase in wages in this country is apparent.

I understand the horsepower per man in England is about one-half that in the United States and the wages are about one-half. The horsepower per man in Japan is about one-fourth that of the United

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[1] "Atlas of U. S. A. Electric Power Industry," p. 10, New York, 1923.

States and the wages are about one-fourth. To compete with cheap-labor countries, where wages paid are about what is necessary to feed a man so that he can do energy-consuming work, it is evident that the United States, without a greater use of power, would be forced to pay the same wages.

W. L. De Baufre,[1] in an address,[2] sums up the situation at the beginning, as follows:

> A century is a very short period in comparison with the number of years man has inhabited this earth. Up to within about a century ago, man truly obeyed the biblical injunction to earn his bread by the sweat of his brow, for the great majority of men and women were slaves or serfs. The Greek and Roman civilizations rested on slavery. Athens had 400,000 slaves to 100,000 free citizens. The industries of Rome were run almost entirely by slave labor.
>
> In the latter days of the Roman Empire, water power became sufficiently developed to compete with slave labor, and "water mills" gradually displaced slave labor in bakeries, in irrigation, and in sawing marble. During the middle ages, mechanical power from water wheels and windmills was applied in grinding grain, in metallurgical processes, and in mining and quarrying, but to a limited extent only.
>
> By the end of the seventeenth century, the coal-mining industry reached appreciable proportions in England and on the continent. As the mines were worked to greater depths, the pumping of water from them became a serious problem. The pumps were operated by horses—as many as 500 horses being employed at one mine for this purpose. The expense of pumping became so great that many mines were abandoned. This situation was relieved by the invention of the steam pumping engine, that of Savery in 1698 and of Newcomen in 1705.
>
> Economic conditions at this time—the first half of the eighteenth century—are indicated by the average wages of a skilled workman in England, about $2.40 a week. Wheat varied from $1 to $1.50 a bushel. Thus, a carpenter or mason could earn only from two to three bushels of wheat for his week's work.
>
> Before the eighteenth century, man used only a few elements of machines and crude combinations of them. In the latter part of that century occurred those great inventions in spinning and in weaving where the skill and intelligence of the workman were transferred to machinery operated by mechanical power. The nineteenth century witnessed the development of machinery with greater than human skill and with but little less than human intelligence, many times multi-

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[1] "Mechanical Power," *Science,* vol. 62, p. 381, 1925.

[2] As retiring president of the Nebraska Chapter of Sigma Xi, on May 15, 1925.

> plying man's productiveness through the utilization of mechanical power . . .
>
> The ancient Greek triremes[1] had 10 marines, 20 sailors, and 170 rowers. Compare this with the airplane carrier Saratoga launched a few days ago, having a crew of 179 officers and 1,695 men and propelling machinery of 180,000 hp. This power is equivalent to that of 2,000,000 galley slaves.

Magnus W. Alexander, president of the National Industrial Conference Board, in analyzing industrial conditions at the close of 1925 and the economic factors likely to play a dominant part in the immediate future, stated:[2]

> Perhaps the most significant, although not the most generally recognized, factor in the achievement of such prosperity as the year 1925 has brought us has been the accomplishment of industry in maintaining a relatively high wage level concurrent with low production costs, resulting in high domestic consumption power. Total production toward the close of 1925 was 42 per cent greater than it had been at the low point of 1924, although only 16 per cent more workers were needed to accomplish this result. Their average "real" weekly earnings are about 25 per cent greater than they were before the war and about 7 per cent higher than at the peak of high wages in 1920. It means for the nation as a whole a larger wealth of goods to enjoy and more capacity to enjoy them, a full purse for the wage earner, with an ample supply of the things he needs or desires at reasonable prices. These are the elements of prosperity.
>
> Improved industrial organization and administration and the steadily increasing use of mechanical power are primarily responsible for the lowering of production costs, and reduced cost per unit of production has made it possible to maintain the existing high wage level without increasing prices and in some cases even permitting price reductions. It is the proper recognition of this fundamental relationship between high wages, low production costs and domestic consuming power, and the application of the principle involved, that largely determine the degree of our future prosperity. It will be a vital factor in continuing our economic progress, even in the face of increasing foreign competition, while maintaining our existing, or even higher, standards of living.

What the foregoing statistics show is that the greater the amount of *available* power there is per worker, the smaller is the unit cost of product to the manufacturer and the higher are the wages paid the worker. Thus, both the manufacturer and the worker profit in proportion to the amount of available power back of each worker. But there is not so much available power per worker per dollar invested when the capacity of a power system is reduced or limited through having to carry magnetizing current that might be produced off the system proper. Hence, low power factor places a burden on the worker as well as on the manufacturer.

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[1] Vessels having three banks of oars.—Editor.

[2] *Electrical World*, vol. 87, p. 126, 1926.

Prosperity increases with the increase of available power and with the decrease in cost per unit of energy.

The cost per unit of energy is increased by power losses and by idle invested capital.

Manufacturing executives are apt to consider the ratio of the unit cost of energy to the unit cost of product, or *vice versa.* What they should do is to compare the present cost of energy with the cost at which energy may be obtained through the elimination of energy wastes. If the prosperity of a nation is proportional to the number of useful horsepower back of each worker, then the more energy that is usefully consumed, the greater also will be the prosperity, both to the manufacturers and the workers, as hereinbefore set forth.

For instance, let the unit cost of energy be $0.40 and the unit cost of product be $4. by ancient methods. Then,

$$\frac{\text{Unit cost of energy}}{\text{Unit cost of product}} = \frac{\$0.40}{\$4.} = 0.10, \text{ or 10 per cent.}$$

By modern methods,

$$\frac{\text{Unit cost of energy}}{\text{Unit cost of product}} = \frac{\$0.04}{\$0.40} = 0.10, \text{ or 10 per cent as before.}$$

But the ratio of the two unit costs of energy is

$$\frac{\$0.40}{\$0.04} = 10, \text{ or 1000 per cent.}$$

The following estimated data[1] for the whole United States tell the story and require no explanation.

TABLE XLVIII.—WHERE THE ELECTRICAL ENERGY WENT IN 1924

PURPOSE	KW.-HRS.
Manufacturing, mining, irrigation, etc	36,700,000,000
Domestic, commercial, and street lighting	12,600,000,000
Lost in transmission	**11,500,000,000**
Electric railways	10,400,000,000
Total generated	71,200,000,000

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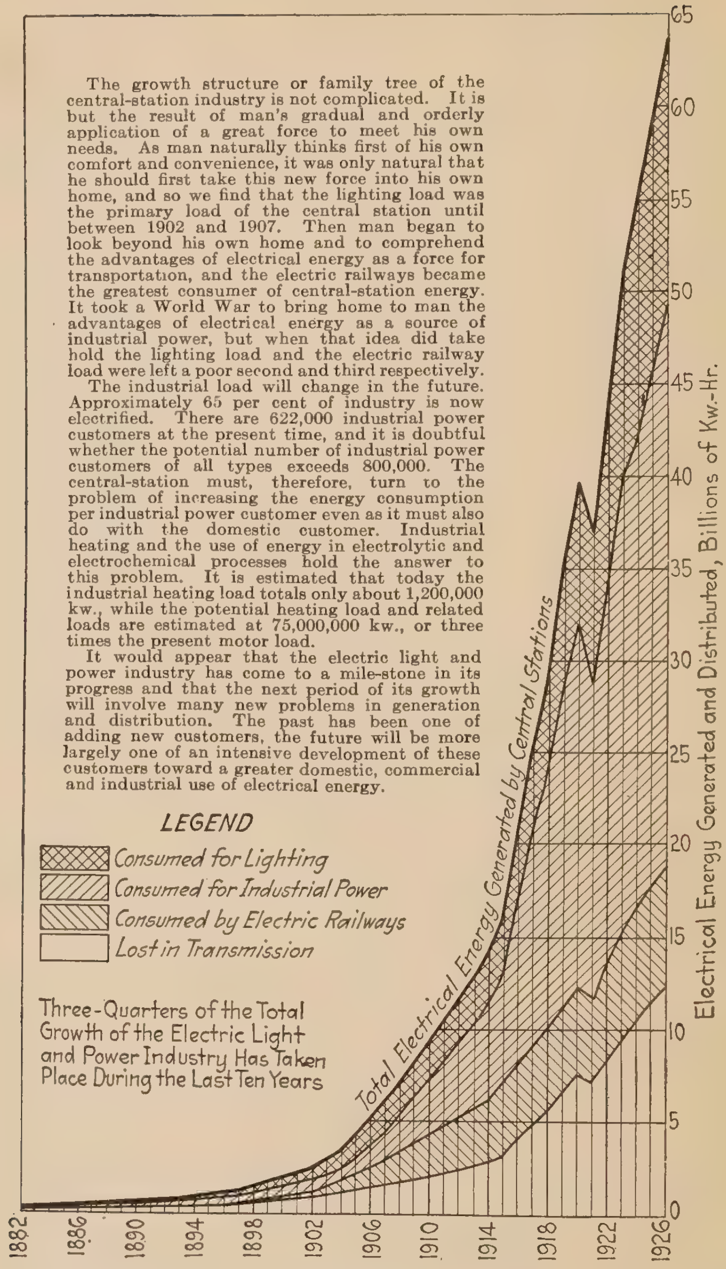
[1] Compiled from data published in *Elec. World*, vol. 87, p. 48, 1926.



The growth structure or family tree of the central-station industry is not complicated. It is but the result of man's gradual and orderly application of a great force to meet his own needs. As man naturally thinks first of his own comfort and convenience, it was only natural that he should first take this new force into his own home, and so we find that the lighting load was the primary load of the central station until between 1902 and 1907. Then man began to look beyond his own home and to comprehend the advantages of electrical energy as a force for transportation, and the electric railways became the greatest consumer of central-station energy. It took a World War to bring home to man the advantages of electrical energy as a source of industrial power, but when that idea did take hold the lighting load and the electric railway load were left a poor second and third respectively.

The industrial load will change in the future. Approximately 65 per cent of industry is now electrified. There are 622,000 industrial power customers at the present time, and it is doubtful whether the potential number of industrial power customers of all types exceeds 800,000. The central-station must, therefore, turn to the problem of increasing the energy consumption per industrial power customer even as it must also do with the domestic customer. Industrial heating and the use of energy in electrolytic and electrochemical processes hold the answer to this problem. It is estimated that today the industrial heating load totals only about 1,200,000 kw., while the potential heating load and related loads are estimated at 75,000,000 kw., or three times the present motor load.

It would appear that the electric light and power industry has come to a mile-stone in its progress and that the next period of its growth will involve many new problems in generation and distribution. The past has been one of adding new customers, the future will be more largely one of an intensive development of these customers toward a greater domestic, commercial and industrial use of electrical energy.

LEGEND
▩ Consumed for Lighting
▨ Consumed for Industrial Power
▧ Consumed by Electric Railways
☐ Lost in Transmission
Three-Quarters of the Total Growth of the Electric Light and Power Industry Has Taken Place During the Last Ten Years
Total Electrical Energy Generated by Central Stations
Electrical Energy Generated and Distributed, Billions of Kw.-Hr.
65
60
55
50
45
40
35
30
25
20
15
10
5
0
1882
1886
1890
1894
1898
1902
1906
1910
1914
1918
1922
1926

FIG. 116.—Evolution of the central station load. (*Electrical World, vol.* 86, *p.* 1087, 1925.)

Under the heading, "Public Pays the Bills," Loyal S. Wright[1] states that "employers have been trying to see how much they can get and how little they can give. Employees, likewise, have been getting without the composite giving, and the public, being human and paying the bills, has felt this condition very keenly, which has resulted in the forming of prejudiced judgments and has torn away some of the concrete of confidence on which the public service corporations must at all times stand. In other words, the books in the mathematics of life are out of balance. Some such spirit as this might be illustrated in the case of a fellow who appealed to the head of an institution for a job. His first question to the employer was, "What will you pay me?" The employer replied that he would pay him all he was worth. The man's answer was, "Nothing doing! I am getting that now."

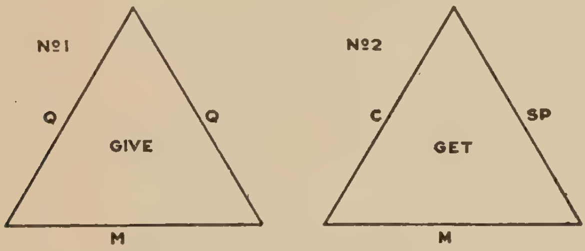


Fig. 117.—Equilateral triangles of service and compensation.

"This 'principle of service' does not stop with the public service corporations. It is a universal principle—one that applies to the animal world, the vegetable world, the mineral world, and even to the banker, and the violation of this principle has and always will mean heavy penalties. Let me illustrate in a simple way the mathematics of life as I see them, by making use of these two triangles:

"Triangle No. 1 has for its right side right quantity of work, right quantity of giving. One naturally expects when he pays for service that the right quantity will be delivered, and a safe rule for all individuals connected with business in order to be sure that this side of the triangle is of the right dimension is to do a little more than is absolutely necessary. The left side of the triangle represents right quality of work or service rendered. The base of the triangle represents the mode or manner in which the work is delivered.

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[1] "The Natural Foundation Laws of Service," an address delivered before the Empire State Gas and Electric Association at Lake Placid, N. Y., Oct. 7, 1921, and published in *Elec. World*, vol. 78, p. 1113, 1921.

"Triangle No. 2 has for its right side the letters *SP*, which mean self-preservation. This is a natural feeling for all individuals, because one of the first thoughts that come to us even in childhood is to preserve and take care of ourselves. The left side of this triangle we will name *C*, which stands for contentment. The base of the triangle we will call *M*, which means money.

"It may be that all three of these states are essential in order to be successful. One must be contented and must preserve himself. And I have never met very many individuals who were 'broke' financially and were exceptionally happy. Money is essential for happiness, therefore, and it is perfectly right and proper that we should strive to accumulate money. In the center of this triangle we will place the word *Get*.

"The Good Book says that the first shall be last and the last shall be first, and it is quite evident that in the attempt to serve the public many institutions and employees have been studying and practicing the teachings of the Good Book, and in the mathematics of life they have put Triangle No. 2 before Triangle No. 1. This is why I say the books are out of balance. This is why I say that we are violating the great natural foundation of service when we try to serve the public with the triangles in the wrong place."

The above is freely abstracted from the address as above reported and surely holds for all of us, individually or otherwise.

If the utilities will do at least what the Philadelphia Electric Company, the American Gas and Electric Company, and some others have done and are still doing, they will overcome operating difficulties to a great extent, ultimately receive a greater ratio of gross revenue to unproductive invested capital, and increase the goodwill of their customers through better service. Rate schedules may have to be adjusted, but that has been done before, and the way to do a thing after it has been found necessary is to go ahead and do it. Every type of power-factor rate has been used successfully even if all are subject to definite criticism; so the necessity of a rate to secure power-factor correction is not a real obstacle to the institution of correction.

If the executive buying power will take a keener interest in the benefits of power-factor correction and will try to appreciate what it means, instructing his plant engineer or his consulting engineer to report on the savings that may be effected by the proper kind of correction, and taking the utility and the manufactures of power-factor-corrective apparatus into his confidence, he will, in a great many cases, receive as rewards saving in his monthly power bills, material increases in the production of his machines in many instances, and other, though intangible, benefits, thus reducing the unit cost of his product.

Competition is going to force prices lower. It must, if Europe is going to pay her debts to us. Any saving which can be proved must be considered by the manufacturer who is going to do a profitable business, or remain in business.

These monetary losses to the power users and the operating difficulties to the utilities, due to low power factor caused by the power users, are constantly increasing in magnitude as industrial and inductive loads increase, and regulation constantly becomes poorer.

No less an authority than W. S. Murray stated in *Electrical World* that "80 per cent of the cost of power to the consumer lies in getting that power to the consumer after it has been generated."

While there may be cases where rates for power should be increased, and other cases where rates should not be decreased, the apparent status is that utility executives, generally speaking, do not intend to offer bonuses or penalties for power-factor correction, except as increasing loads reach the limit of capacity or they reach the position of facing compulsory rate reductions because of excessive earnings, and that commercial men of the utility companies hold before themselves the colossal bugaboo what they call the practical impossibility of handling power-factor-correction rate schedules with the chief offending class of customer—the consumer using, say, 100 kw. and less. There appears to be nothing more of real consequence to the problem.

If figures mean anything, nearly everybody in the utility companies must be perfectly conscious of the general excessive capital investment and the magnitude of the economic waste involved, but it is also believed that many of them are trying to comprehend what the discussion is all about. Public service commissions have a duty to perform in this direction, namely, seeing that the economic waste is stopped for the benefit of the consumer at large.

Surely commercial executives of the electric public utilities must recognize that sooner or later they will have to put correction across, but they apparently await orders from the top. The utility engineers know how and where to make power-factor correction to stop the wastes. The engineering means for correcting these wastes are at hand and entirely adequate to a solution of the problem. Suitable meters will be produced when there is a sufficient demand for them, but it is to the interest of the meter manufacturers to study this phase of the problem more thoroughly and solve the meter situation. Supply may either create or follow demand. It is believed that the alleged difficulty of explaining magnetizing current to the power user is due either to the lack of understanding of those trying to explain it or else it is an artificial attitude pending the clarification of company policies higher up.

It should constantly be borne in mind that power-factor correction pays both the utilities and their customers, as has been fully explained herein by some of their executives. It is a matter of mutual interest and is purely a business proposition. Proper service to the community, of reasonable cost and high quality, is the business of a utility. It has been stated by a high executive that each company, when rate reductions are in contemplation, will see the importance of making rate reductions to the alternating-current customers dependent upon a good power factor. The statement by the same executive that the power-using consumer, whether he be a large power user or a small power user, does not want to be troubled about anything except his own job which is to produce or market something, towards which the use of alternating current is necessary, or expedient, is very true. To the author-editor's personal knowledge, gained through experience, there must be a great many manufacturing executives who not only do not know what the power factor is but do nothing to reduce the payments therefor although everything is clearly stated in the rate schedule and contract, even in cases where penalties are enforced or bonuses given. Furthermore, not all of the utilities enforcing penalty clauses advise all of their customers thus penalized to improve their power factors.

The author-editor is very sympathetic with the central stations in the point of view as to where the responsibility for correction lies, namely, on the power user. A truly just rate schedule would include a penalty on every customer whose power factor does not closely approach unity, and this penalty should sharply increase as the power factor decreases from that value, or an equivalent bonus or discount should be instituted which would operate the same way as the penalty. A very small magnitude of the capital cost of correction on the customers' premises is apparent relative to the tremendous magnitude to the central stations for supplying the magnetizing current.

Class discrimination, as between the large and small power users, is about as bad as class legislation. There is much discussion about superpower brought forth by the vast networks that now, or surely will, connect the cities, towns and farms, and operate about 40 per cent or more of the railroad mileage of the eastern territories. There is the slogan "Conservation of the Natural Resources." The slogans "Conservation of Energy" and "Conservation of Capital" also should be freely used and practiced. With the amount of electric energy lost in transmission in 1924 greater than the electric energy consumed by the electric railways, and equal to 91 per cent of all of the electric energy consumed in domestic, commercial and street lighting, all over the United States, or equal to one-half the total consumption of all central-station energy sold outside the industries, or to one-half of that purchased from the central-station companies for industrial use, the time has arrived when these enormous economic losses must be reduced. Power from the St. Lawrence, where more than 5 million horsepower of 24-hr. power now run to waste, is the mutual dream of the farmers and the power companies, for canal and dam, and no doubt it will be realized. The Federal Power Act permits and encourages power development from rivers flowing through the public lands of the Great West, and there are other projects. It is estimated that 49 million horsepower, or roughly one and one-half times as much as runs the industries, is required to run the farms of the United States, about one-half being animal power. However, internal-combustion engines have a large field here. Every time the power company enlarges its field of operation it enlarges its field of obligation. How will all this affect the economic waste due to low power factor, as the waste increases in proportion to the new electric generating and motor-operating kva. installed, and will the farmer constitute another class?

The *Electrical World* stated editorially in the January 9, 1926 issue, under the title, "Rural Service Bugbears:"

> It is now reasonably easy for the farmer to get electric service if he lives within striking distance of a distribution system. It is also comparatively easy to secure the co-operation of farmers in an attempt to work out an equitable and satisfactory rural service supply. Education and enlightened public relations have brought these changes and notable progress has been made.
>
> But there are still many utility companies that evade the rural service problem and regard with trepidation, not to say actual horror, the surely coming day when the farmer will demand as his right the opportunity to participate in the comforts and aids that electric service gives to human beings. Several reasons are back of this attitude and cause this fear. Ignorance of the possibilities of rural service, contentment with present conditions, fear of unprofitable investments, inertia and horror of the rate goblin that leers around the corner all combine to bring about an unenlightened attitude toward rural service. These utilities are missing an opportunity to establish themselves as real assets in their communities. By their opposition to rural service they are building a wall without stability, and their situation will be serious in the coming years when other utilities in other localities have marched ahead to a solution of the rural service problem and they have been left behind to meet the blows of a dissatisfied public.
>
> Every far seeing utility will co-operate with farmers to the utmost in order to develop rural service, farmers are intelligent beings, and if financial handicaps in specific cases prohibit rural service they will be willing to recognize the facts. If rates need adjustment and the new rates are based on a sound economic analysis, the farmers will approve them. There is nothing to fear in the rural service business if co-operation, initiative and vision are brought to bear. There is much to fear if utility companies do not help to bring about rural electric service.

The above editorial might have referred to the present power-factor situation. And while marching forward, sometimes it is well to pause and look back. Often a new perspective is gained thereby.

The railroads, supplanting the stage coach and canal, began as small lines, then interconnected and merged into great systems. But the automobile, local and interstate bus, and the motor truck have changed the former "last word" in transportation.

According to statistics (page 278) as of 1924, published in *Electrical World,* private electric generating plants furnished 37.5 per cent of the 31 billion kw.-hr. consumed by all industries of the United States; the remaining 62.5 per cent being purchased from central-station companies. Hence the private plants generated 60 per cent as much electrical energy for industrial use as was purchased from the central-station companies.

In an editorial in the December 24, 1925, issue of *Electrical World* the question is asked, "Should Central-station Companies Buy Surplus Industrial Power?" This article referred to industries which require a great deal of process steam and relatively little power, and it quoted Joseph Pope of Stone & Webster, Inc., as pointing out at the recent fuel and power meeting of the Affiliated Technical Societies of Boston that this is undoubtedly the Utopia of conservation, but that there are many real obstacles to be overcome before it can be reached.

In this connection, it is interesting to note that one unaflow engine manufacturer claims that over 200 contracts have been made whereby the engine has been required to pay for itself in the saving effected against other steam engines and central-station rates. It should be remembered that unaflow engines have attained steam rates of 14 lb. per hp.-hr., when running non-condensing. Will the Diesel engine, with its claimed ability to do from three to six times the work of a steam engine for the same cost of fuel, making about 60 per cent of the heat developed useful where hot water and low-pressure steam are required in the industries, eventually increase the percentage of electrical energy generated in private plants and become the "industrial flivver," as well as the prime mover of some of the non-hydro central stations?

In a survey made by *Power*[1] it is shown that the reciprocating stationary steam engine is holding its own in the industries and will continue to do so for a long time to come. Table XLVIII shows the distribution by type of total number and total horsepower reported, of stationary engines built from 1920 to 1924.

There is a normal annual production of about 600,000 hp. of five principle types; about 20,000,000 hp. being installed in manufacturers, mines, utilities, and buildings at this writing.

The majority of steam engines installed in the past five years have been for auxiliary drive, fan, compressor and like services rather than for power generation. For prime mover use the steam engine will continue to find an active field where non-condensing operation is desired and where there is no use for bled steam, inasmuch as the reciprocating engine is generally conceded to have a better thermal efficiency under such conditions than has its competitors.

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[1] January 5, 1926, page 16, vol. 63.

Table XLVIII

	Four-valve Releasing	Uni-flow	Single-valve Automatic	Single-valve Throttling	Four-valve Non-releasing	Others and Unclassified
Per cent total number	8.7	14.4	17.2	52.2	4.6	2.9
Per cent total horsepower	39.6	15.2	15.0	12.5	10.9	6.8

The steam engine is successfully competing with electric motors in certain fields, as above outlined.

The year 1925 was distinguished by much activity in the internal-combustion engine industry, both in the introduction of new designs and in the expansion of the commercial use of existing types.

The high-speed oil engine still remains unborn in this country, although several German firms are producing miniature heavy-oil engines for automobile and truck service, even including a unit for motorcycles. In England, William Beardmore & Co. have developed a Diesel for rail-car service, weighing less than 12 lb. per brake horsepower. Several American builders are developing high- and medium-speed engines, but none is prepared to make public announcement, the engines still being in experimental stages.

The desirability of such engines for rail cars and buses is apparent, and the transcontinental and return non-stop runs of the Canadian Northern car equipped with the Beardmore engine are illustrative of the capability of the oil engine to operate continuously at high speed.

The Diesel locomotive has apparently come into its own; already four railroads have such units on order or in operation. In one instance this type locomotive has been adopted in preference to electrification, inasmuch as the purchase of the units can be made as the traffic increases, thereby avoiding an excessive initial investment. Locomotives so far constructed consist of 300-hp. and 1,000-hp. solid-injection engines, with electrical transmission to the driving axles. The 1,000-hp. locomotive is especially interesting inasmuch as the engine used is an inverted V-type with opposing pistons connected to two crank shafts carrying gears meshing with the driving shaft.

The stationary or power-plant field has always absorbed the majority of oil engines of both small and large capacities. During the year a number of units of over 1,500 hp. have been installed, several going into electric lighting plants. Florida towns of miniature size have developed almost overnight into cities of the first class. To meet the enormous increase in power demands, many of these cities have installed Diesels, among these being Hollywood-by-the-Sea where an original installation of a 1,250-hp. Diesel has been augmented by two 2,200-hp. units. Other Florida installations include Fernandia, Cocoa, Sarasota, South Tampa, Kissimmee, Perry, Lake Worth and Jacksonville . . .

Many ice and cold-storage plants have installed Diesels; usually, however, the engines are below 300 hp. in rating, although below is shown an Santa Fe R. R. icing station with two 500-hp. units, the ice machines being motor driven. A unit consisting of the compressor cylinder, mounted upon the frame of the horizontal engine has found considerable favor in ice plants, inasmuch as both the first cost and the floor space are reduced . . .

One of the wonders of the engineering world is the number of oil engines ranging from about 200 down to 10 hp. that are installed each year. In the face of decreasing costs of purchased energy the volume of sales of the semi-Diesel has shown a marked increase each year . . .

An application of the internal-combustion engine, which, while not new, has shown a decided increase, is breakdown service. This is a complete reversal of form from the situation some 15 years ago, when the reliability of the gas and oil engine was so questionable that some other stand-by equipment was deemed necessary. At present, in many industries where energy is obtained over long transmission lines, gas- and oil-engine stand-by units are becoming common. This is very apparent in the telephone field, in the mining field, in municipal works and other industries where stoppage cannot be permitted. One manufacturer of gasoline engines places almost his entire output in such service.

The manufacturing business is not monopolistic, excepting as to patents, and so forth, as the central-station business necessarily must be, nor is it controlled by any regulatory commission. The manufacturing business, with its distribution service, is conducted on the basis of competition. When two manufacturers of the same kind of particular product have their own private electric generating plants and one is underselling the other, if the latter finds that the former's production is increased and his rejections decreased through the smoother running of his machines, reduced power bills, and other benefits, due to increasing the power factor right inside his plant, which is the only place where it can be corrected or increased, the chances are that he will follow suit and do all other things necessary to reduce the unit cost of his product, for he knows that in the long run he must meet competition or go bankrupt.

While there is some competition between central-station companies, there is much competition between the central stations and the private electric generating plants, as shown by the above figures.

Power sales will be greatly facilitated and more private generating plants abolished if the central-station companies will guarantee to institute power-factor correction, both through free tests and advice for remotoring and free power-factor corrective equipment, on the new customer's premises upon the signing of an agreement by the new customer that he will remove his generating equipment from his premises. This will pay both parties to the contract for the correction will cost the new customer nothing but will give him benefits that, otherwise, he might feel he could not afford, while the central-station company also would receive the benefits of released feeder and transformer capacity and a proportionate decrease in its operating difficulties, thereby enabling it to give better service. And another steam engine and generator would be scrapped. The utility always is glad to be rid of one of these rate makers. The statements of L. R. Nash in Art. 126 may be profitably read in this connection.

The large power user has long been an outstanding contributor to the development of the central-station industry and the extension of its service to the smallest households of the city, town and farm. To him is due a just rate with inducements which will cause him to aid in the reduction of the vast economic waste due to low power factor. If there is to be any discrimination at all it should be the reverse of what it is now, for with cheaper power there will be greater prosperity and all can afford the conveniences and luxuries which electric service brings to the home where money is spent—not earned.

In the words of Theodore Dwight:[1]

> Executives of private enterprises are constantly striving to improve the efficiency of their power plants by seeking to increase the use of current for light, heat and power in industrial plants. A central station which sells current for lighting only will find that the major part of the equipment is idle during the greater part of the twenty-four hours, and is only earning a return on its high cost for a brief hour or two daily. As public service commissions can require that the revenue

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[1] "Superpower," by W. S. Murray, p. 23, McGraw-Hill Book Company, Inc., New York, 1925.

of utilities shall be limited to a figure which will give only a certain fixed return on investment, every user benefits from efficient and economic management in the lowering of rates.

The enormous investments of the electric public utilities include additional generating equipment, synchronous apparatus in substations, additional copper (or aluminum) in lines, transformers, and distribution systems—and the return on the investment, as fixed by the public service commissions, is thereby increased over what it would be if much of the capacity was released for productive purposes. With proper correction, this expensive equipment can be used with less losses and will give better service until the loads increase to the full productive capacities of such lines and equipment and without the further purchase of more such equipment for the same purpose. Synchronous apparatus or static condensers will long be used where lighting loads predominate because of the large numbers of idle transformers and small motors that must be supplied with magnetizing current.

And the manufacturing executive has an obvious duty to perform, primarily for his own benefit but also for the common good. Almost anyone can tune a radio set to the frequency of the broadcasting station, and knows very well from experience that sharp tuning is necessary for best results. Power-factor correction consists in tuning motors and transformers to the frequency of the power system. If this frequency is 60 cycles per second, tune the motors and the transformers to 60 cycles per second. The basic principle is common to both.

Most industrial plants are out of tune—the small power user's equipment interferes with good reception by the large power user who made possible the reduction of cost to the small power user.

Good public relations should start with industrial power and, as R. F. Pack so justly stated in an interview reported in the January 2, 1926, issue of the *Electrical World:*

> Good public relations are like Christianity, a matter of personal contact. No laws and no resolutions have ever made a good Christian, and exactly in the same way, one by one, the citizens of this country must be reached, informed, fairly treated and their confidence gained by good service rendered with a courteous regard for their undeniable rights and with a proper sense of the obligations the companies owe those whom they serve.

With private ownership of the electric public utilities by more than 2,000,000 citizen stockholders, and with wise executive management, enterprise, vision, courage, and good public relations, prosperity will increase for all.

But unnecessarily wasted energy, idle invested capital, with its high cost to the consumer, and poor service, with its disastrous effects on production, are costly retarding influences.

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